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NO. 420 VOL. 49

# The Journal of THE ROYAL AERONAUTICAL SOCIETY

THEY WHO LOOK AHEAD

*For I dipt into the future, far as human eye could see,*
*Saw the Vision of the world, and all the wonder that would be;*
*Saw the heavens fill with commerce, argosies of magic sails,*
*Pilots of the purple twilight, dropping down with costly bales.*
Tennyson's "Locksley Hall"

Painted by W·James for

# Helliwells Ltd.

PART OF BRITAIN'S AIRCRAFT INDUSTRY

HEAD OFFICE: OLD TOWN, STRATFORD-ON-AVON

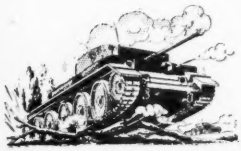
HALF A CENTURY OF KEEPING FAITH

ESTABLISHED 1889

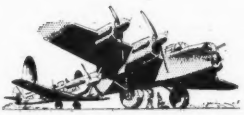
FIFTY YEARS OF PROGRESS

FUNGIMUR EIS QUAE PROMISIMUS

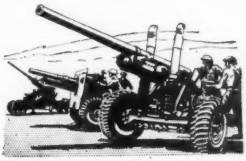
# *Contributions by* DUNLOP



Rubber-tyred wheels for tanks were developed by Dunlop, who produced nearly 1,000,000 for all types of tanks and transport vehicles.

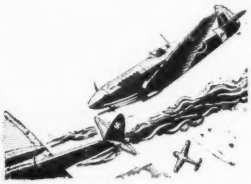


The majority of R.A.F. fighters, bombers, transports and gliders had tyres, wheels and brakes designed by Dunlop. Dunlop tyres and wheels were standard equipment for 71 types of British aircraft.



Dunlop pioneered pneumatic tyres for guns and produced the bulk of the British Armies' requirements during the war.

The famous track-grip style tyre tread adopted by the Services for almost every type of wheeled transport was originated by Dunlop in 1926.



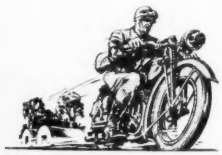
Every enemy 'plane shot down by a British fixed-gun fighter was destroyed with the aid of Dunlop gun and cannon firing mechanism.

To prevent escape of petrol, and fire after damage, thousands of British aircraft were fitted with petrol tanks covered with special types of rubber materials evolved by Dunlop.

Sand tyres used by the "Immortal Eighth" in chasing Rommel out of Africa were evolved in 1930 by Dunlop and made in huge quantities throughout the war.

Dunlop made 100,000 rubber dinghies for air-crews and more than 1,000,000 life-belts for sailors, soldiers and airmen all over the world.

Dunlop produced millions of respirators for the Fighting Services, Civil Defence and the Home Front from 1937 to 1945.



The War Office standard of performance for motor-cycle tyres was set by the Dunlop "Universal," evolved in 1935.

Dunlop undertook the production development of barrage balloons in this country and produced 60 per cent. of the total output during the war period.

"Bullet-proof" and "Run-flat" tyres for fighting vehicles were outstanding features of Dunlop production. Dunlop made hundreds of thousands

H1/162

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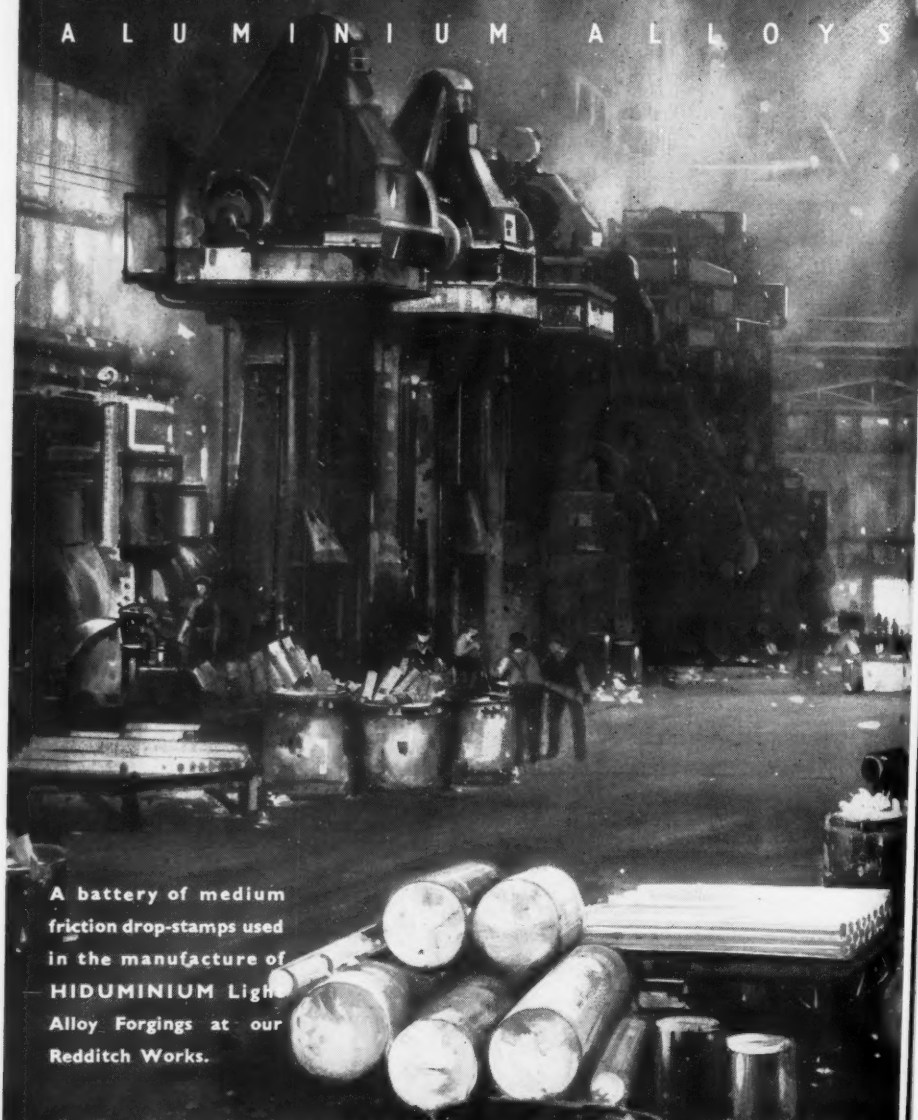

A battery of medium friction drop-stamps used in the manufacture of HIDUMINIUM Light Alloy Forgings at our Redditch Works.

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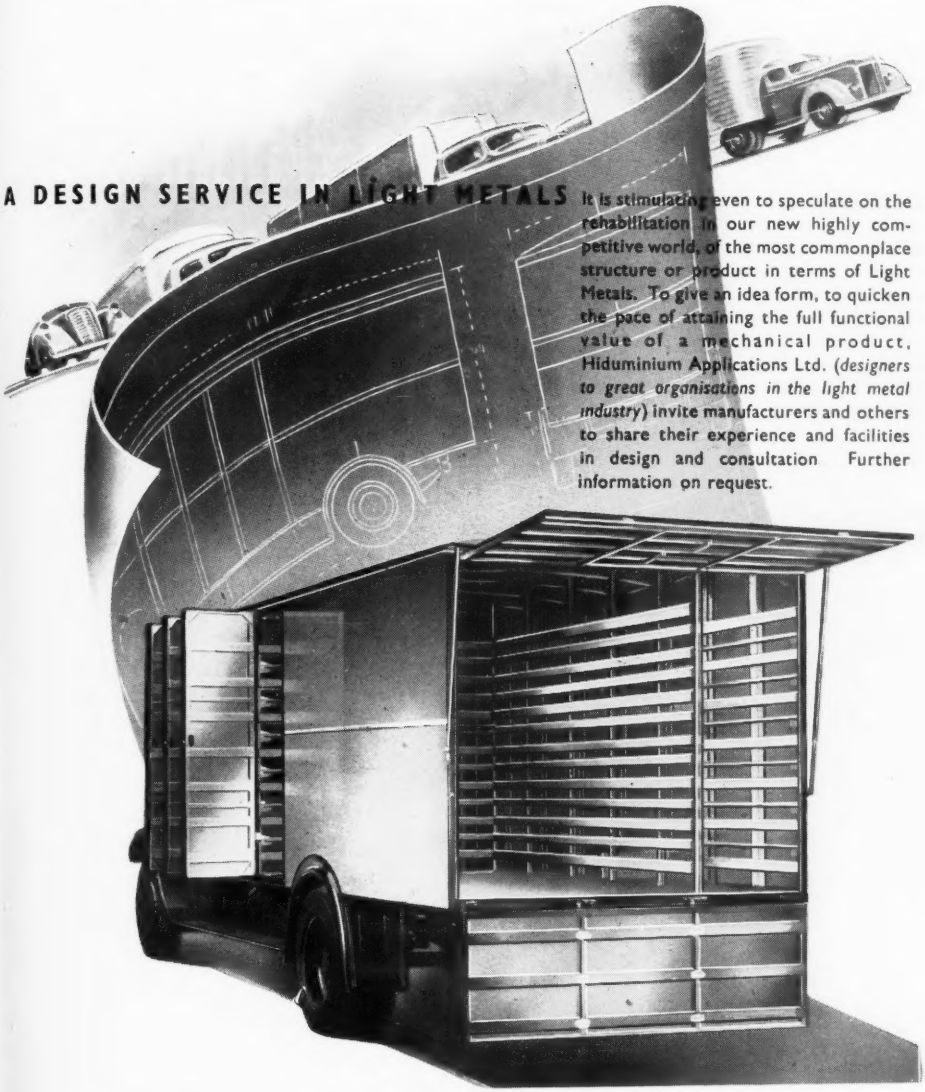
*For the Motor Vehicle Designer*



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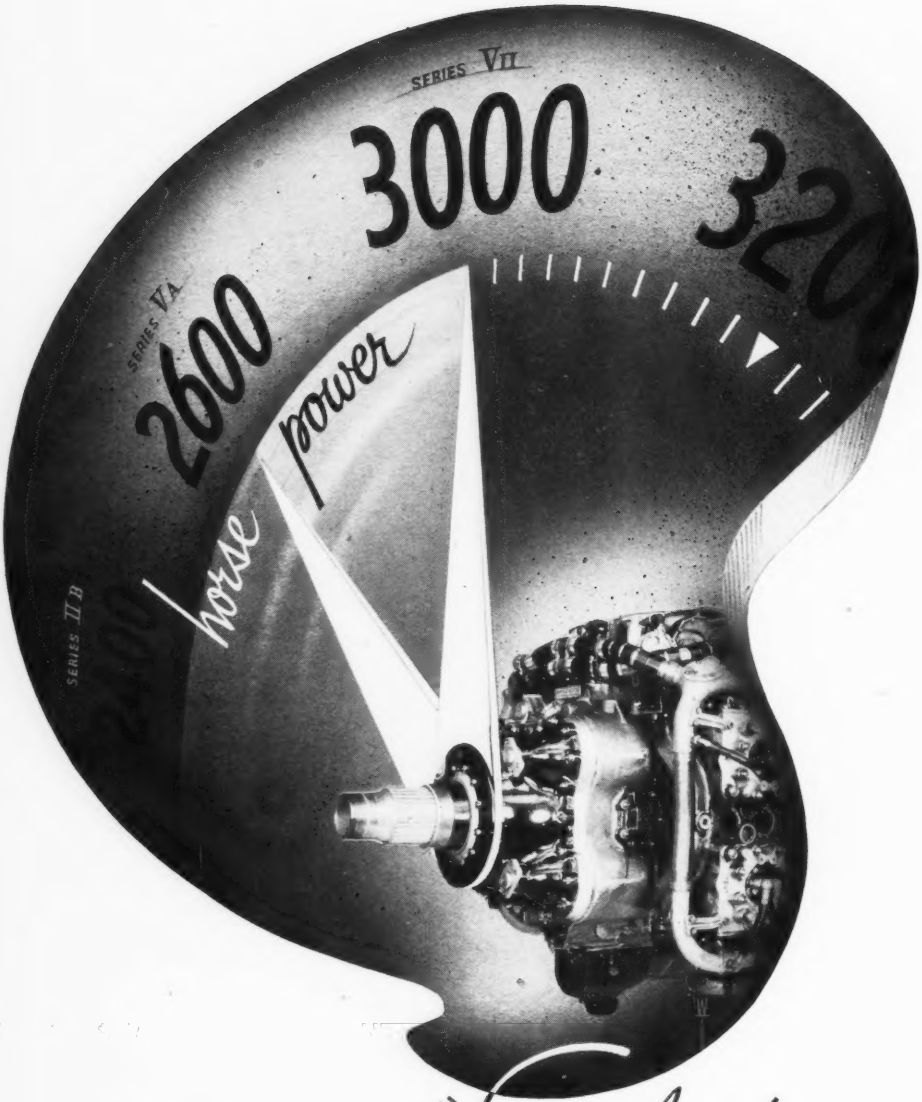


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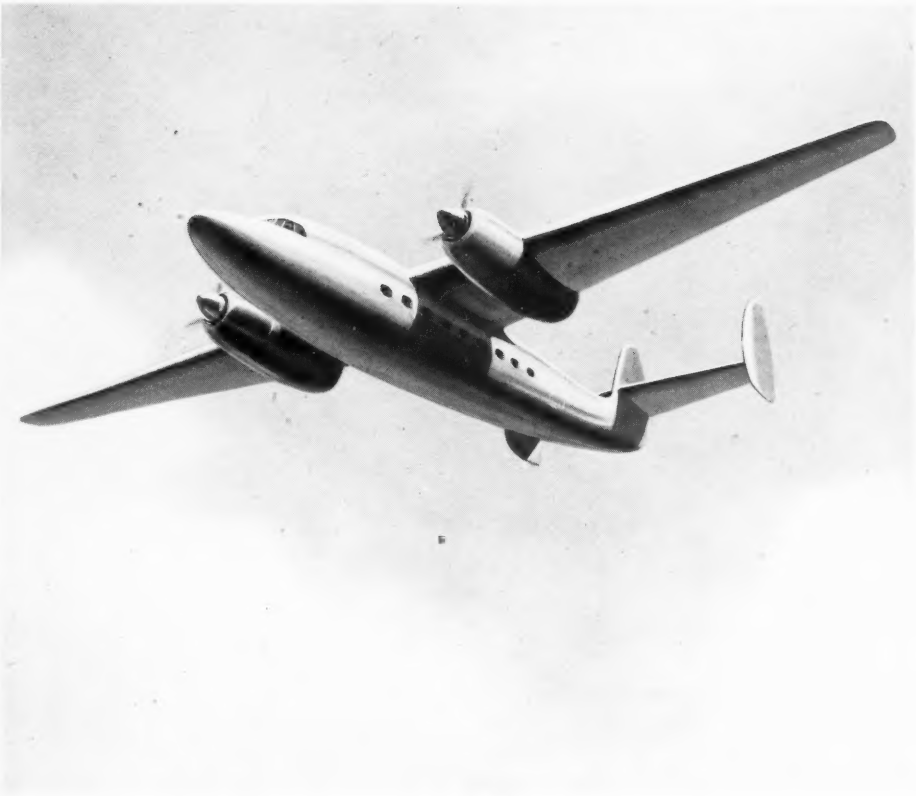

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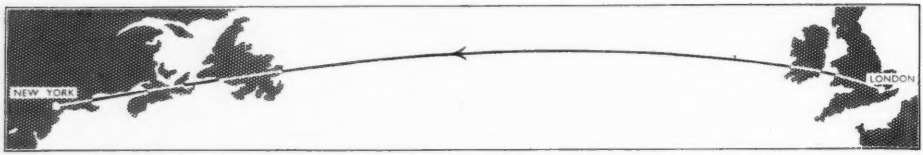
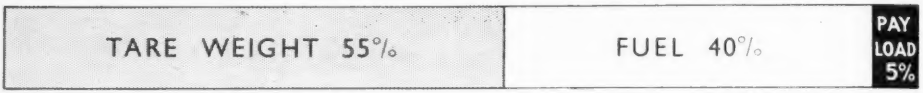



.... an ordinary passenger aircraft must, on the westward journey, carry fuel for 4650 still air miles ....




.... which restricts the payload to a very small proportion of the gross weight.

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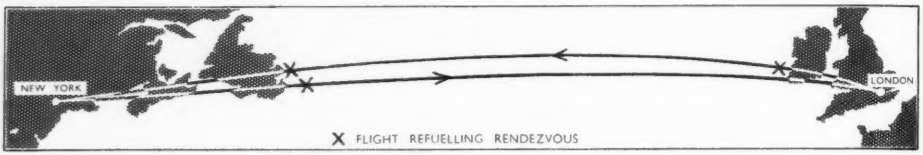
On the same route, with flight refuelling ....




.... a similar airliner, with full safety allowances would need to carry fuel for only 2300 still air miles ....

.... thus the payload can be trebled by means of refuelling in flight.

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**With which is incorporated The Institution of Aeronautical Engineers**


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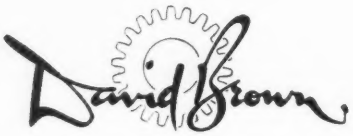


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# DECEMBER NOTICES 1945

## JOURNAL PREMIUM AWARDS

**The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members (or non-members) will contribute papers on their own special subjects.**

### An Appeal to Members

The Society is very anxious to have as complete a record as possible in its files of the work of its members. Such a record will enable the Society to be of greater use to its members and to know, particularly, those members who can help the Council and its Committees on problems which are under discussion.

It would be appreciated, therefore, if members would bring their records of work and employment up to date; and in future notify headquarters of any change of job or position in a firm. In most cases the records held by the Society do not go beyond the date of election as Fellow, Associate Fellow or Associate, and often, therefore, are some years out of date.

The Council are forming a number of technical committees and wish to draw upon the best talent among its members in order that the most authoritative reports may be presented.

### Contents of the December Journal

The Future Scope of Propellers, by L. G. Fairhurst, A.M.I.Mech.E.

### Society's Eightieth Anniversary

On January 12th, 1946, the Society celebrates the 80th anniversary of its foundation. The Council propose to celebrate the event and members will receive notices later in the month of the form the celebrations will take.

### Eightieth Anniversary Souvenir

Early in January there will be published an illustrated souvenir of the history of the Society since its foundation on January 12th, 1866. This is the first time such a full history has been prepared. Owing to the restrictions on paper only a limited edition can be published and members are advised to apply early for their copies. The price will be five shillings.

### Christmas Holidays

The Library and Offices will be closed from Monday, December 24th, 1945, to Thursday, December 27th, 1945.

### Lecture Programme

The following are the forthcoming lectures. Members are admitted without tickets, but non-members must obtain tickets through a member.

The Lectures will be held at 6 p.m. in the Lecture Hall of the Institution of Civil Engineers, Great George Street, S.W.1 (by permission of the Council of the Institution). In each case tea will be served at 5.30 p.m.

December 19th—Atomic Disintegration, by Professor N. Feather, F.R.S.

January 31st—The Application of Radio to Civil Aviation, by Sir Robert Watson-Watt, C.B., Ll.D., F.R.S., F.R.Ae.S.

February 13th—Selection of Engineering Personnel for the Aircraft Industry, by Mr. F. Holliday, B.Sc., F.P.S., A.F.R.Ae.S.

**Branch Lectures**

BELFAST BRANCH

January 15th—Stability and Control, by Mr. J. Graham, G.I.Mech.E., Grad. R.Ae.S.

February 12th—Radio Aids to Navigation, by Mr. S. N. Johnson.

March 12th—Model Tank Testing of Flying Boat Hulls and Floats, by Mr. L. Smith, A.F.R.Ae.S.

BIRMINGHAM BRANCH

January 16th—Civil Aviation—the Extent to which it may Supplement or Supersede Surface Transport. Discussion will be led by Sir Frederick Handley Page, C.B.E., F.R.Ae.S., and held in the Birmingham Chamber of Commerce, 95, New Street, Birmingham, at 7 p.m.

BRISTOL BRANCH

January 8th—The Choice of Materials for Aircraft Construction, by Dr. B. Chalmers, Ph.D., F.Inst.P., Head of Metallurgy Division, Royal Aircraft Establishment.

January 29th—Brains Trust and Debate.

February 1st—Dance at the Victoria Rooms, 8.30 p.m.

February 19th—Reading of Prize-winning Papers by Junior Members.

All meetings will be held in the Conference Room, Bristol Aeroplane Co., Ltd., Filton House, at 6.30 p.m.

MEDWAY BRANCH

January 14th—The Design Team and How it Works, by Mr. R. Boorman, F.R.Ae.S., A. W. S. Clarke, D. Keith-Lucas, A.F.R.Ae.S.

To be held in the Mathematical School Hall, Rochester, at 6 p.m.

January 17—Dance at the Town Hall, Chatham, from 7.30 to midnight.

GRADUATES' AND STUDENTS' SECTION

January 3rd—Auxiliary Services, by Mr. P. L. Cronbach, Grad.R.Ae.S.

January 23rd—Low Drag Aerofoils, by Mr. L. G. Whitehead, Ph.D., B.Sc., A.F.R.Ae.S.

February 7th—Discussion.

To be held in the Library of the Society at 4, Hamilton Place, W.1, at 7.30 p.m., unless otherwise stated.

**Corrections to Paper on "Some Notes on Vibration Analysis," by R. G. Manley, B.Sc. (Graduate). (Journal Vol. 49, pp. 419-426.)**

We regret that the following errors occurred in the printed text of this paper:—

p. 422. Second column, lines 5 and 6, replace

$$X_L \text{ by } x_L.$$

p. 424. First column, line 19, to read

$$S_{pr}=\frac{\Sigma\,(X_jF_j)_r}{Q_r\Sigma\Sigma\,(b_{hk}X_hX_k)_r}$$

Second column, line 13, to read

$$T=\frac{m}{8}\cdot[(\dot{x}_1+\dot{x}_2)^2+3(\dot{x}_1-\dot{x}_2)^2].$$

Second column, line 24, to read

$$\left[\frac{A_1}{A_2}\right]=Fk\,\frac{\left[\dfrac{18-5L}{-(2+L)}\right]}{12-16L+3L^2}$$

p. 426. First column, line 23, to read

$$\ldots \text{ Also } \lim_{Q\to Q_r} Lt\,|\,C\,|/(Q-Q_r).$$

Second column, line 6, to read

$$\ldots\ldots E=\int N dz.$$

Second column, line 7,

$$\ldots N=Fz/Z.$$

**Election of Members**

The following were recently elected members of the Society:—

*Associate Fellows*

Leslie Stuart Ash, Kenneth Brooks Ayers, Ludwik Seweryn Bialkowski, Thomas Alec Brown, Thomas Ralph Brown (from Companion), Alexander Kenneth Clyde, Eric Cyril Cosserat, Leonard William Crowther, Thomas F. Francis, Ellis Joseph Gabbay, Sydney Owen Norman Garland, Thomas Day Griffin (from Graduate), Arnold Alexander Hall, Sydney Thomas Melling

(from Associate), Peter Robert Mossman, Alfred Robert Mortimer, John Frank William Parry, Allan Drury Pepper, Bhup Chand Puri, Albert Rose (from Student), Harold John Saker, Charles Frederick Sarsby (from Associate), Richard James Clifford Tarr, George Fred Parkhurst Trubridge (from Companion), William Hastings Wallbanks, Francis John Watts (from Graduate), Harold Edward William West, Charles Walter Harry Wright.

*Companions*

Maurice Robert Crocker, Douglas Meddick Marrs.

*Associates*

Thomas Cambell Beswick (from Graduate), Horace Montague Bright, Norman Brown, Hugo Victor Benjamin Burgerhout, Arthur Edward Callard, Frederick Robert Carter, John Henry Carter, John Churchill Claydon, Edgar John Codwell, Charles Cope, George Cordrey (from Student), Benjamin Gordon Couch, William Ernest Crockford, Ebenezer Doyle, Edwin William Elliott, Harry Fisher, Norman Grosvenor Garner (from Student), Bertram John Godwin, James Hepburn, George Hinkley, Ralph Clair Hoewing, Charles Herbert Hutber, Robin Leslie Hutchins, Dennis Arthur Jacques, James Lewis, Norman Berry Littlejohn, Ernest Allan Mace, Victor Louis Maniez, Arthur Dudley Marshall, Robert Maun, Robert William Molyneux (from Companion), Charles George Buchanan McClure, John Danford de Salis McElwain, Robert Gordon Macleod (ex-Student), Joseph Gaston Naz, Francis James O'Hara, Frank Phripp, Raymond Keith Plumer, Cyril Alphonso Pugh, Frank James Purnell, John Rushworth, Bertram Beresford-Shead, George Arthur Shirley, Arthur Harvey Smith, George Colin Spratt, Edgar Thomas Stephens, Joseph Stevens (from Student), George Arthur Symons, Harold Thring, Richard Toner, Frederick John Ward Turner, Daniel Webb, Gilbert Edwin Welbourn, Ian Alexander MacKenzie-Williamson, Raymond Douglas Yandell.

*Graduates*

Mohammed Mostafa El-Alaily, Ronald Herbert Peter Barber, John Albert Beard, James Francis Berry, Anthony Herbert-Caesari (from Student), Frank Thomas Davies (from Student), Sabodh Chandra Das, Sydney James Garvey (from Student), Francis Henry Keast, Donald Louis Mordell, Kenneth William Newby, Ralph Lovell Edwin Toms (from Student), Peter Cranbrook Trounce, James Carey Wallin (from Student) Arthur Adrian Willett, Bernard Wild (from Student), Frederick Peter Youens.

*Students*

Douglas Raymond Andrews, Peter Beaumont, John Michael Bennett, Hugh Osborn Bissett, Gerald Spencer Blackman, Michael Booth, Lionel Louis Branch, Derek George Brown, Peter Foster Catling, Herbert Edgar Chappel, John Charles Chicken, Kenneth William Course, William Arthur Crago, Geoffrey Miles Cutting, Ronald Leonard Dack, Andrew James Duxbury, Gordon Cowan Eddie, Terence William Frederick Fairbairn, Peter Lawrence Edward Gallimore, Vernon Frederick Gardener, Albert William Grattidge, Raymond William Edward Graham, Robert Charles Godwin, John Stanley Greenhalgh, Victor Ransford Haas, Lewis Henry Wilson Harris, Stephen John Taylor Harvey, Derek Vance Hilborne, John Laurence Horne, Doreen Howell, Brian James Jeffery, Wilfred James Kelly, Charles Richard Kidd, Peter King, Peter Stanley Lamb, Kenneth William Charles Lavanchy, Douglas Edward Lewis, Alan Donald Littlechild, Graham John Macrae, Kenneth John Mackenzie, John Cecil Martin, Geoffrey William Morris, James John Pearson, Derek James Perry,

Edward Alfred Piper, John Leonard Raynes, David Alexander Rodger, Gordon Edwin Staples, John Charles Thorpe, Robert Longley Trillo, Alan James Troughton, Ronald Thomas Turner, Philip Edward Burdock Vaile, Keith Claude Walker, Geoffrey Wass.

**Honorary Companion**

The Council at their meeting on November 13th elected Mr. A. N. D. Smith an Honorary Companion of the Society in recognition of his work as Honorary Accountant of the Society for the past fifteen years.

**Additions to the Library**

Pamphlets in italics with location reference following in brackets. Books marked * or ** may not be taken out on loan.

B.a.351.—*De Havilland Vampire Jet-driven Interceptor Fighter. De Havilland Public Relations Dept.* 1945. (Y.3.iii.39.)

B.a.352.—*De Havilland Hornet Long-Range Fighter. De Havilland Public Relations Dept.* 1945. (Y.3.iii.40.)

B.a.353.—*Vickers (Supermarine) Spitfire XXI and XXII. Ministry of Aircraft Production.* 1945. (Y.3.iii.41.)

B.a.354.—*New British Airliner. (Vickers Viking.) Society of British Aircraft Constructors.* 1945. (Y.29.iii.)

B.a.355.—*Great Britain's First Post-war Tailless Aircraft. (The Handley Page Manx.) Society of British Aircraft Constructors.* 1945. (Y.29.iii.)

B.f.90.—Bird Flight for Bird Lovers. By Jack Parham. Harborough Publishing Co., Ltd. 1945. 7/6.

D.a.A.42.—*Domestic Air Carriers. Civil Aeronautics Board, Washington, U.S.A.* 1945. (Y.37.7.)

D.a.A.43.—*Convair Production. Consolidated Vultee.* 1945. (Y.37.8.)

D.a.D.1-2.—*Air Information. (In French.) Nos.* 44, 45. *Ministre de l'Air.* (Y.6.iii.)

D.a.D.3.—*Bilan d'une annee de travail et taches d'avenir de l'aviation Francaises. Charles Tillon.* (Y.6.iii.)

D.b.243.—The Civil Air War. C. G. Grey. Harborough Publishing Co. 1945. 12/6.

D.b.244.—*Institute of Transport Presidential Address. (On Civil Aviation.) Sir Frederick Handley Page.* 1945. (Y.6.ii.)

D.d.31.—*The Scientific Civil Service: Reorganisation and Recruitment. H.M. Stationery Office.* 1945. 3d. (PE.2.b.22.)

E.f.110.—Aircraft Inspection Methods. N. C. Bartholomew. Pitman Publishing Co. 1943. 7/6.

EE.b.84.—Aircraft Power Plants. Arthur P. Fraas. McGraw-Hill. 1943. 27/-.

EE.c.76.—Aircraft Engines. Vol. I. Second Edition, revised and enlarged. A. W. Judge. Chapman & Hall. 1945. 28/-.

EE.d.10.—The Stromberg Flow Bench. Charles H. Fisher. George Newnes, Ltd. 1944. 3/6.

EE.h.15.—Jet-propelled Aircraft. Model Publications, Ltd. 1945. 2/-.

G.a.75.—Materials and Structures. Vol. I. E. H. Salmon. Longmans, Green & Co. 1945. 21/-.

G.e.A.99.—*The Production of Aircraft Stampings. High Duty Alloys.* (PG.3.a.17.)

I.c.21-29.—Applied Mathematics and Mechanics. (In Russian.) (Precis in English.) Vol. 8, Nos. 1-6; Vol. 9, Nos. 1-3. Moscow. 1944-45.

L.f.13.—The Chichester Star Compass. Francis Chichester. Allen & Unwin. 1945. 5/6.

L.g.24.—Norie's Air Tables. George P. Burris. Imray Laurie Norie and Wilson. 1944. 15/-.

L.g.25.—Astro-Navigation Tables for the Common Tangent Methods. E. E. Benest and E. M. Timberlake. W. Heffer & Sons. 1945. 7/6.

L.k.49.—Aviation Neuro-Psychiatry. R. Ironside and I. Batchelor. Livingstone. 1945. 8/6.

M.c.70.—*Radar. Published in the U.S.A. by the Government Printing Office. Reprinted by H.M. Stationery Office.* 1945. 1/-. (PM.2.8.)

N.a.85.—Atomic Energy: A General Account of the Development of Methods of Using Atomic Energy for Military Purposes under the Auspices of the U.S. Government. Published in the U.S.A. by the Government Printing Office. Reprinted by H.M. Stationery Office. 1945. 2/6.

N.a.86.—*Statements Relating to the Atomic Bomb. H.M. Stationery Office.* 1945. 4d. (PN.1.a.12.)

Q.d.62.—What Shall I Do After the War? (Careers.) E. Hawks. Ellison Hawks, Ltd. 1945. 7/6.

R.c.282.—A Compendium of Aviation and Aerostation. H. Hoernes. Chas. Griffin. 1911.

R.c.283.—Istoria Vozdukhoplavaniya i Aviatsii v S.S.S.R. (Russian History of Aviation.) V. A. Popoff. Moscow. 1944.

S.e.103.—The War in the Air: Bombers. E. Hawks. Real Photographs, Ltd. 1944. 7/6.

S.e.104.—The War in the Air: Fighters. E. Hawks. Real Photographs, Ltd. 1943. 5/-.

S.e.105.—The War in the Air: More Fighters. E. Hawks. Real Photographs, Ltd. 1944. 5/-.

S.e.106.—Air Transport Auxiliary. Published by the Air Transport Auxiliary (1945). 2/6.

S.e.107.—Warship Recognition. (Section on Aircraft Carriers.) Real Photographs Co., Ltd. 1945. 3/-.

S.e.108.—Find, Fix and Strike. Terence Horsley. Eyre & Spottiswoode. 1945. 9/-.

S.e.109.—Bombers' Battle. (Anon.) Duckworth. 1943. 10/6.

S.e.110.—Men of the R.A.F. Sir William Rothenstein. Oxford University Press. 1942. 12/6.

S.e.111.—Second Report of the Commanding General of the U.S. Army Air Forces to the Secretary of War. Published in the U.S.A. by the Government Printing Office. Reprinted by H.M. Stationery Office. 1945. 1/6.

S.e.112.—" I Couldn't Care Less." Anthony Phelps. Harborough Publishing Co. 1945. 8/6.

TT.a.51.—Gone for a Burton. Arthur Gwynn-Browne. Chatto & Windus. 1945. 10/6.

**Acknowledgments**

The Council acknowledge with thanks the gift of photographs and lantern slides from Boulton Paul Aircraft, Limited, and photographs from Sir W. G. Armstrong Whitworth Aircraft, Limited. They would also wish to acknowledge the return of back Journals from the following Members:—

Mr. J. D. Campbell (Associate Fellow).
Mr. T. E. H. Beck (Student).
Mr. J. A. C. Williams (Associate Fellow).
Mr. R. F. Samuels (Associate).
Mr. P. M. Travers-Clark (Associate).
Mr. John Finnigan (Student).
Mr. Ian M. Strachan (Student).

J. LAURENCE PRITCHARD,
*Secretary.*

# THE FUTURE SCOPE OF PROPELLERS

*by*

**L. G. FAIRHURST, A.M.I.Mech.E.**

***Mr. Fairhurst was apprenticed with Leyland Motors in 1919, and entered the Design and Research Department in 1923. Before joining Rotols as Assistant Designer in 1937 he spent two years with Bristol and three years with Rolls-Royce on engine and propeller design. He became Chief Designer in 1940, and since 1941 has been Chief Engineer.***

A MEETING of the Royal Aeronautical Society was held in the lecture hall of the Institution of Mechanical Engineers, Storey's Gate, St. James' Park, Westminster, S.W.1, on Thursday, October 4th, 1945, at which a paper on "The Future Scope of Propellers," by Mr. L. G. Fairhurst (Chief Engineer, Messrs. Rotol, Ltd.), was presented and discussed. In the Chair, Sir Frederick Handley Page, President of the Society.

THE CHAIRMAN, introducing the speaker, said that some people who were interested particularly in jet propulsion considered that the future scope of propellers was distinctly limited. Others took a rather different view; therefore, Mr. Fairhurst's views on the subject would be interesting.

*Introductory.*

With the rapid advances made during the war in the power output of piston engines, together with the introduction of straight jet and gas turbine units, the time is very opportune to consider the future scope of the propeller as an efficient means of aircraft propulsion on the types envisaged for the future.

The aircraft designer has taken full advantage of these advances in power unit development by introducing aircraft with ever improving aerodynamic characteristics, thus enabling these increases in power to be utilized efficiently.

The propeller designer has been fully cognisant of these combined developments, and in meeting them has had to make rapid strides in research and development throughout the war period.

In examining the future scope of propellers it is as well to review first the rate at which aircraft and engine development has proceeded over the last six years, as this development would never have been achieved in this space of time had it not been for the intervention of war. As such, it has forced the propeller designer to consider seriously his future at an earlier period than would otherwise have been the case.

# THE FUTURE SCOPE OF PROPELLERS

It will be generally appreciated that the subject in question is one of a most controversial nature, since it is deeply involved with the transitional stage between the piston-engine and gas turbine as a future aircraft propulsion unit. As the latter unit is relatively in its infancy a considerable amount of conjecture cannot be avoided which adds further fuel to the controversy.

With this in mind the author has attempted to deal with the issues involved on a broad basis, and wherever possible to bring in accomplished facts without recourse to highly technical jargon. In this he hopes that the reasoning will be of a sufficiently practical nature to be appreciated by people who are not in daily contact with technical matters appertaining to propellers but who, nevertheless, have every bit as much interest in its outcome.

*Summary.*

The following paper on the Future Scope of Propellers is an examination of the application of the propeller as a means of aircraft propulsion over the next five years.

The paper is prepared in progressive stages dealing firstly with the types of propellers envisaged for various future installations of piston and gas turbine engines of 1,000 h.p. upwards, followed by detail considerations of the problems which face the propeller designer both aerodynamically and structurally in meeting the demands of the aircraft and engine designer. The paper concludes with a specification of the future propeller and with a short forecast of the types of propellers for the smaller types of aircraft.

With reference to the gas turbine engine, it will be appreciated that due to the relative infancy of this unit the author has had to forecast a possible range of engine powers in order that the propeller application to each can be considered. Further, in calculating propeller performance it has been necessary to create a curve showing the probable diameter of body behind the propeller for the range of powers under consideration.

As it is the problem of ultra-high speed flight at high altitude which taxes to the greatest extent the ingenuity of the propeller designer, a considerable part of the paper deals with this subject.

The following is a summary of the leading points dealt with in the paper:—

Propellers for piston engines up to 5,000 h.p. at varying altitudes up to 40,000 ft. and a speed of 550 m.p.h.

Straight jet with propeller as thrust augmentor.

Gas turbine propellers from 1,000 h.p. to 10,000 h.p. at altitudes of 10,000 and 40,000 ft.

Aerodynamic development for high speed flight at high altitude.

Two speed engine reduction gears.

Propeller blade materials.

Single-hub propeller limitations.

Counter-rotating propellers.

Co-axial propellers.

Propeller weights.

De-icing.

Braking propellers.

Vibration problems.

Propeller synchronization.

Propellers for engines between 100 and 1,000 h.p.

Future specification for propellers.

*Conclusions.*

As a result of examining each of the above problems the author concludes as follows:—

(1) *The limit of the efficient use of a propeller* as a means of aircraft propulsion will firstly occur on fighter aircraft with a 4,000 h.p. piston engine developed at 40,000 ft. at a forward speed of 550 m.p.h.

(2) *Beyond* 550 *m.p.h.* and considering mainly forward speed as the criterion, the straight jet will replace the engine/propeller combination.

(3) As a possible *thrust augmentor* for straight jet installation the propeller will still remain a serious competitor to other forms of thrust augmentation.

(4) *The gas turbine/propeller* combination will become increasingly favourable over the next five years for multi-engined bombers and multi-engined commercial aircraft. Powers up to 10,000 h.p. at 40,000 ft. with a forward speed of 400 m.p.h. can be catered for with a propeller.

(5) *Propellers over the next five years* will be extended to counter-rotating six (3+3), eight (4+4) and ten (5+5) bladed types.

(6) *Aerodynamic development* in both wind tunnel and full scale flight of an intensive nature is essential on improved high speed aerofoil sections to maintain good propulsive efficiencies up to a speed of 550 m.p.h. Special attention to root shapes at the spinner periphery is further essential, particularly to ensure efficient air flow around the entry duct of gas turbines.

(7) *Counter-rotating propellers* will become universal for upwards of 2,500 h.p. piston engines in the high-speed fighters on account of the increased aerodynamic efficiency and greatly improved aircraft handling characteristics. They may become universal on turbine engines in order to reduce the degree of swirl and turbulence created in front of the air entry duct, and also to enable a small diameter of propeller to be used and hence a short undercarriage. Essential development consists of:—

Investigation of compressibility effects by wind tunnel tests, flight tests and spark photography.

Measurement of torque division for various differential pitch settings, for both positive and negative values of pitch, by wind tunnel and flight test.

Measurement of thrust and torque for braking conditions (negative pitches), by wind tunnel test.

Investigation of performance and vibration aspects of pusher counter-rotating installations, by wind tunnel and strain gauge tests.

General investigation of optimum planforms and pitch distributions, etc., by wind tunnel and flight tests.

(8) *Braking propellers* will be universally adopted on flying-boats, multi-engined bombers and commercial aircraft. Their requirements will be even more pronounced on turbine engined and possibly straight-jet engine installations on account of the greater overall cleanliness of such aircraft and their use of tricycle undercarriages.

(9) *Propeller blade materials.*

*Hollow steel blades* should eventually replace all other types on multi-engined aircraft, mainly on the score of better durability. Whether it will be possible to get down to thickness/chord gradings of around 16% at the spinner periphery, or provide the extreme dimensional accuracy demanded for high speed sections is as yet speculative.

*Duralumin blades* will continue for the time being as the blade material for the high speed fighter class, but will be severely taxed in reducing the thickness/chord grading at the spinner to below 20%, especially on piston engines.

*Compressed wood blades* will require very considerably improved surface coverings if they are to approach the durability of duralumin and even more so, hollow steel.

*Solid steel blades* offer possibilities in super thin aerofoil sections and should be capable of obtaining 16% thickness/chord grading at the spinner. Their application may be more successful on certain sizes of turbine engines; their use being largely dictated by the progress of development in the reduction of the vibration levels.

(10) *Propeller weights* for alternative blade materials. As long as the compressed

wood blade can be fitted directly into a hub primarily designed for a duralumin blade the former must always be the lighter propeller.

The duralumin bladed propeller will only compete with its wood bladed counterpart when the root size of the former is reduced to a point which excludes the direct fitment of a wood blade, demanding a heavier hub to house the latter. There is little doubt that with development the fatigue and .1% proof strength properties of duralumin will eventually be increased to this point.

The hollow steel blade with its relatively small hub will definitely exclude the direct fitment of a wood blade, and as such will offset on the complete propeller a considerable amount of the saving, blade for blade, between wood and steel. For the larger sizes of 15 ft. upwards the hollow steel bladed propeller will come out considerably lighter than the duralumin bladed type.

(11) *Engine vibration.* Intensive development between the piston engine and propeller designer on reduction of vibration levels is of the utmost importance, as otherwise the piston engine will always carry the disability of a propeller somewhat below the optimum aerodynamic efficiency.

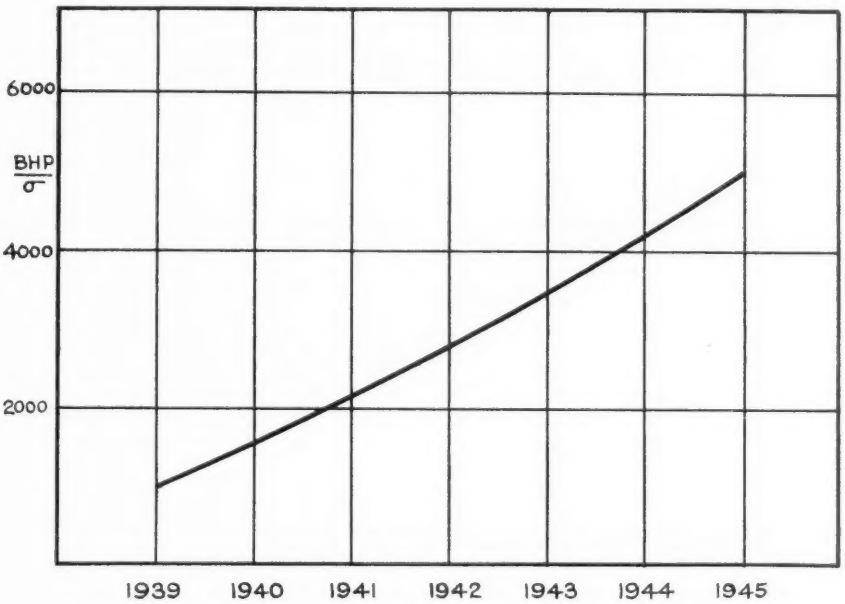



FIG 1 : INCREASE IN $\frac{BHP}{\sigma}$ FOR PISTON ENGINE FULL THROTTLE PERFORMANCE DURING THE WAR YEARS

(12) *Noise.* It is essential that the concerted efforts of the aircraft, engine and propeller designer should be directed towards a clear understanding of the problems involved and the reduction in noise level of the components contributing to these problems.

(13) As the main problems associated with the future scope of propellers are aerodynamic and mechanical in order of severity, the time is now opportune for a most intimate collaboration between aircraft, engine and propeller designers.

It should now be fully appreciated that if the propeller is to continue as an efficient means of aircraft propulsion it should have equal priority in the early design and development stages with the airframe and engine. Furthermore, equal development facilities in the nature of hangar testing and flight testing to those of the airframe and engine manufacturers should be afforded when the quantity of prototype aircraft and engines are being scheduled.

Fig. 1 indicates the increase in engine power and operational altitude starting at a value of B.H.P./$\sigma$ of 1,000 in 1939 and increasing to 5,000 in 1945. It has been found necessary to employ the parameter B.H.P. divided by relative density in order to cater for the effect on altitude of change of boost in a piston engine. Fig. 2 shows the increases in fighter aircraft speed over this period from 300 m.p.h. in 1939 to 460 m.p.h. in 1945.

The diagram following, *i.e.*, Fig. 3, shows the development which the propeller designers

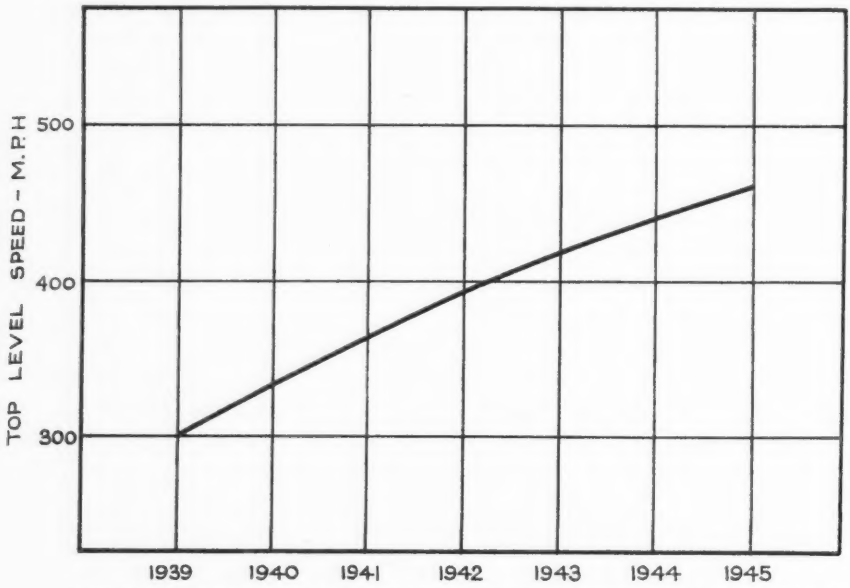



FIG 2 : INCREASE IN AIRCRAFT SPEED DURING THE WAR YEARS

Finally, it is the author's hope that the paper will not only serve to forecast the future scope of the propeller, but in indicating to the aircraft and engine designer the factors governing its future will enlist their help and guidance in achieving such objectives, particularly in the gas turbine class.

## WAR TIME REVIEW

The war time development in fighter aircraft and engines is shown in the first two diagrams, Figs. 1 and 2.

have carried out over this period to meet the aircraft demands, commencing in 1939 with the three-bladed propeller and carrying on through the four and five bladed propellers to the six blade (double-three) counter-rotating propeller.

In the bomber class of aircraft the stringent propeller requirements imposed by high speed and high altitude have not been nearly so critical as with the fighters, the main developments consisting of a change from three-bladed to four-bladed propellers on the

grounds of handling increased engine powers efficiently, and also the introduction of the fully feathering propeller as a universal feature.

## PISTON ENGINE POWER PLANTS ENVISAGED OVER THE NEXT FIVE YEARS.

The first essential before considering the propeller aspect is to formulate some idea as to the types of piston engines over the next five years.

does not suggest that 5,000 h.p. is the limit of the piston engine, this figure being merely a forecast of the power which the propeller designer will have to meet within the next five years.

The aircraft application of such engines will most probably consist of:—

(*a*) Single seater fighter up to 4,000 h.p. with ultimate speed of 550 m.p.h.

(*b*) Bomber and commercial transport up to 5,000 h.p. with speeds of 300 to 400 m.p.h.

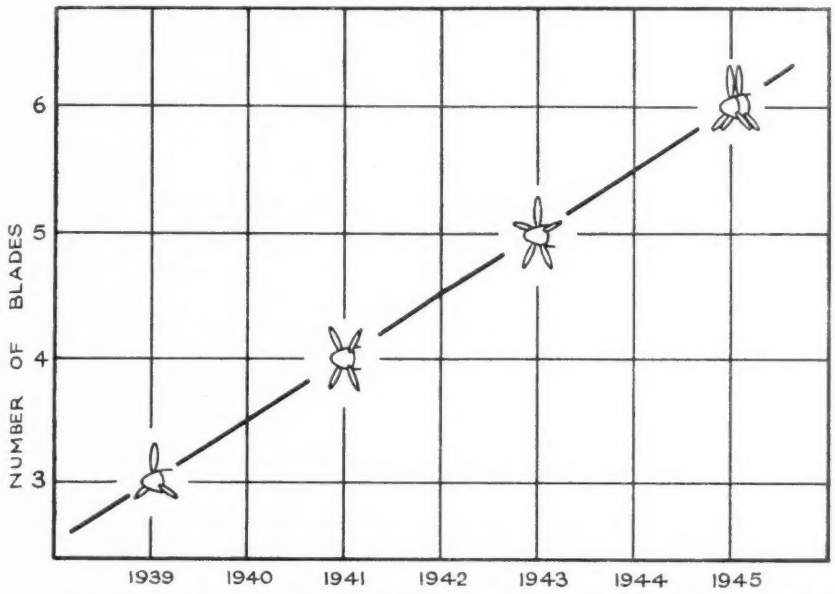



FIG 3 : DEVELOPMENT OF PROPELLER TYPES DURING THE WAR YEARS

The end of the European war has taken us up to powers of 2,400—2,800 h.p. on both air-cooled radial and liquid-cooled in-line engine types. It is very likely that development of these particular engines will go ahead up to 3,200 h.p. by the use of methynol water injection, but for powers beyond this figure a new range of engines will be required.

The next stage under consideration is a range of engines of basically 3,000 h.p., capable of development up to 4,000 h.p., and a further basic type of 4,000 h.p. capable of development up to 5,000 h.p. The author

The former aircraft is limited at 4,000 h.p. as it is not considered practical to house a piston engine power plant of any higher power in a machine of this class. The latter aircraft may use piston engines in a single unit up to 5,000 h.p., although in aircraft of such size there is a tendency to bury the engines in the wing and take the power out of two independent units coupled to a co-axial propeller, each unit feeding one half of the propeller.

To be definite about the operational altitude of such aircraft is very difficult, as in the military cases this is largely dependent upon

current tactical requirements; in the commercial aircraft the pros and cons of high altitude operation are still under consideration.

In view of this the diameters of such propellers are presented in graphical form showing the requirements from sea-level to 40,000 ft.

The diagram, Fig. 4, shows this trend of propeller types and diameters envisaged to cover these conditions, ranging from six

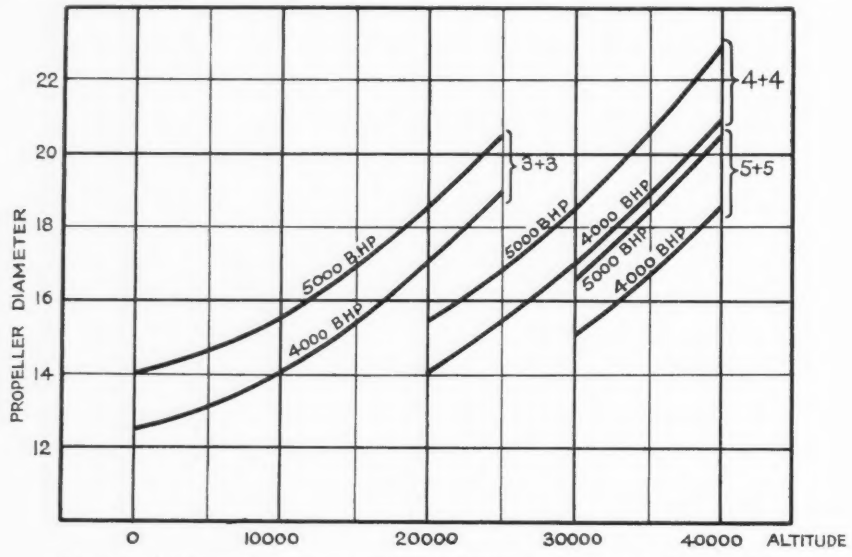



FIG 4: DIAMETERS FOR PISTON ENGINE TYPES AT 500 M.P.H

blades (3+3) counter-rotating to ten blades (5+5) through diameters from 13 to 22 ft.

It can be seen that for a single engined fighter of 4,000 h.p. developed at 40,000 ft. with a forward speed of 550 m.p.h. would demand a propeller of ten blades approximately 16 ft. diameter; this being considered the practical maximum diameter for an aircraft of this type.

These recommended propellers are so far based on mere aerodynamic considerations. Later in the paper the question of their practicability on the grounds of weight, bulk and controllability are examined.

## JET AND TURBINE UNITS

As the turbine unit relative to the piston engine is as yet in its infancy, it can only be conjecture if one is to envisage the types and sizes of power plants which will be adopted for aircraft during the next five years.

It is firstly advisable to classify these units into:—

(*a*) Straight-jet with propeller as thrust augmentor.

(*b*) Gas turbine engine and propeller.

Dealing with the problems associated with each in turn:—

(*a*) *Straight-jet with propeller as thrust augmentor.*

In an aircraft deriving its sole means of propulsion from a straight jet, inferior efficiencies are inherent at low forward speeds, giving rise to relatively poor take-off and initial climb characteristics.

The combination of propeller and jet unit wherein something of the order of 20% of the unit power is made available for the propeller may possibly be adopted as one means of reclaiming the loss in take-off and initial climb performance.

It is estimated that by using a propeller as

thrust augmentor, the take-off and initial climb of the aircraft would be improved by 45 to 50%. It must be clearly understood, however, that this comparison is between a straight-jet installation where the turbine is designed without consideration of a propeller, and an installation where the turbine is so designed to provide a certain percentage of the total power of the unit for the propeller.

With such a propeller the problem of control arises, and to which of the operating conditions, *i.e.*, forward speed, thrust, or engine r.p.m. the propeller is to be responsive will considerably tax the ingenuity of both engine and propeller designers.

In a normal constant speed propeller on a piston engine the propeller is designed to absorb the full engine power, and is responsive to changes in engine r.p.m. through the medium of an engine driven governor, and having a pitch range sufficiently adequate to handle the full range of power and r.p.m. of the engine.

In the jet unit installation in question, as the propeller would be designed merely to handle a small portion of the total unit power, control of the propeller by a governor responsive to unit r.p.m. may give unsatisfactory constant speeding characteristics on the take-off and initial climb. In a normal piston engine installation under conditions of take-off and climb, the propeller starts in a temporarily fixed pitch condition. As the aircraft slowly gathers speed the propeller in this condition absorbs less power, and if the propeller remained in fixed pitch overspeeding would result. The fact that the propeller is under governor control responsive to r.p.m. prevents this condition arising by automatically coarsening the pitch to suit the forward speed.

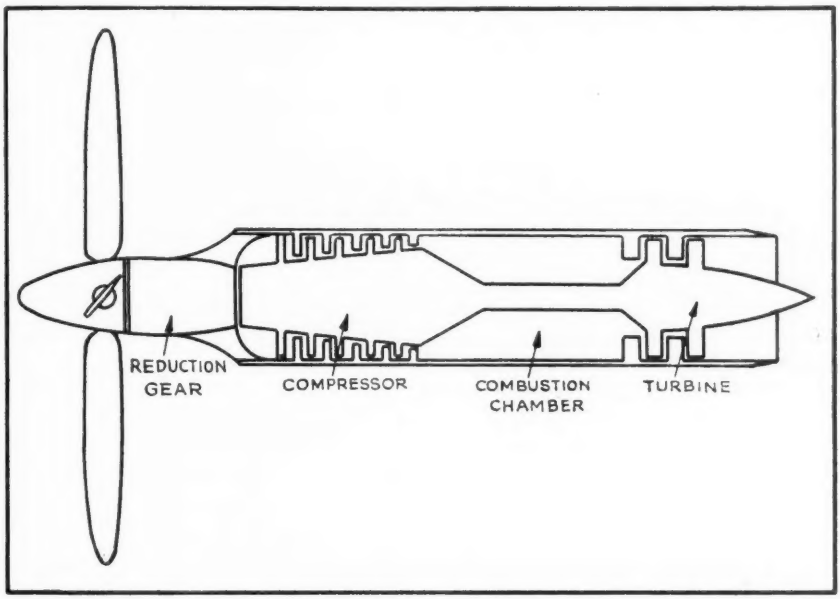



FIG 5: DIAGRAMMATIC LAYOUT OF JET ENGINE WITH PROPELLER AS THRUST AUGMENTOR

In the jet unit installation in question, the reduction in power in the propeller as the aircraft gathers speed is only a very small percentage of the total unit power, and it is, therefore, questionable whether the rotational

speed of the whole propeller/turbine/compressor system would increase sufficiently to permit the governor to apply the requisite correction.

A further problem is the neutralizing of the propeller at all-out-level condition of the aircraft. If the propeller were to remain in the pitch taken up after initial climb was completed, a heavy drag would be induced on the aircraft and seriously impair its speed. Hence the possible requirement for some alternative means to the present form of propeller constant speeding control.

(*b*) *Gas turbine engine with propeller.*

The combination of gas turbine and propeller will, with little doubt, be the stage immediately following the piston-engined aircraft, and will be used in aircraft such as multi-engined bombers and commercial airlines of the freight and passenger carrying class up to a maximum speed of 400 m.p.h.

The propulsion unit will consist of the usual compressor, combustion chamber and turbine, the latter driving the propeller through a reduction gear as shown diagrammatically in the sketch, Fig. 5.

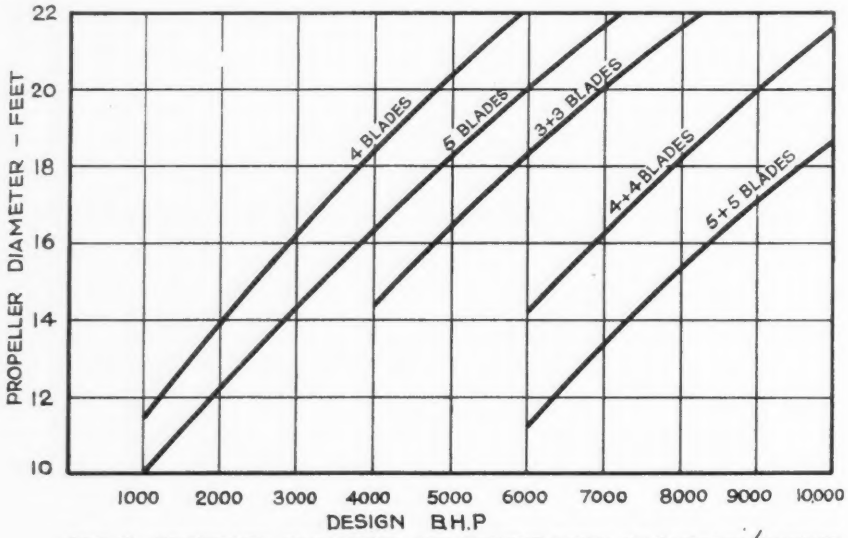



FIG 6: PROPELLER DIAMETERS FOR TURBINE TYPES AT 300 M.P.H/10,000 FT

The best system may be to provide a separate turbine to drive the propeller, to which the propeller could be made responsive without having any reference to the main turbine. This would ensure satisfactory constant speeding on take-off and climb, and the neutralization of the propeller at top speed could be carried out by feathering.

As little or no practical data is available on such problems, the author would welcome the views of engine designers, as the use of the propeller as a thrust augmentor is entirely dependent upon the solution of these problems.

Approximately 80% of the unit power will be allotted to the propeller, the remaining 20% issuing in the exhaust gases as kinetic energy.

In considering a range of turbine-propeller units the author would expect to see powers of 1,000 h.p. to 10,000 h.p. over the next five years.

Operating altitudes of 10,000 and 40,000 ft. have been considered, as these are the most likely extremes to be met covering the non-pressurized and pressurized aircraft.

The propeller application to such units is

shown in the following diagrams, Figs. 6, 7, 8, and 9.

From an examination of the diagrams, Figs. 6, 7, 8, and 9, it will be readily seen that no difficulty at all is likely to be experienced in catering for powers up to 10,000 h.p. at 10,000 ft. Indeed, the largest diameter necessary is 18 ft. for the optimum case, which could be reduced to 16 ft. without seriously affecting the efficiency.

It is obvious, however, that a more difficult problem confronts the designer at 40,000 ft., especially at the lower speeds. Here optimum diameters of 30 ft. are required which even if reduced to, say, 27 ft., will still present a serious problem to the aircraft designer in providing sufficient space in the installation. It is not foreseen, however, that any insuperable difficulties will arise from the propeller side in designing and building propellers of these sizes.

An interesting point which can clearly be seen from these curves is the very large saving in diameter which can be effected by increase in the number of blades. At 5,000 h.p. at 40,000 ft., for instance, a diameter saving of the order of 10 ft. can be achieved by changing from a single four-bladed to a ten-bladed (5 + 5) counter-rotating propeller.

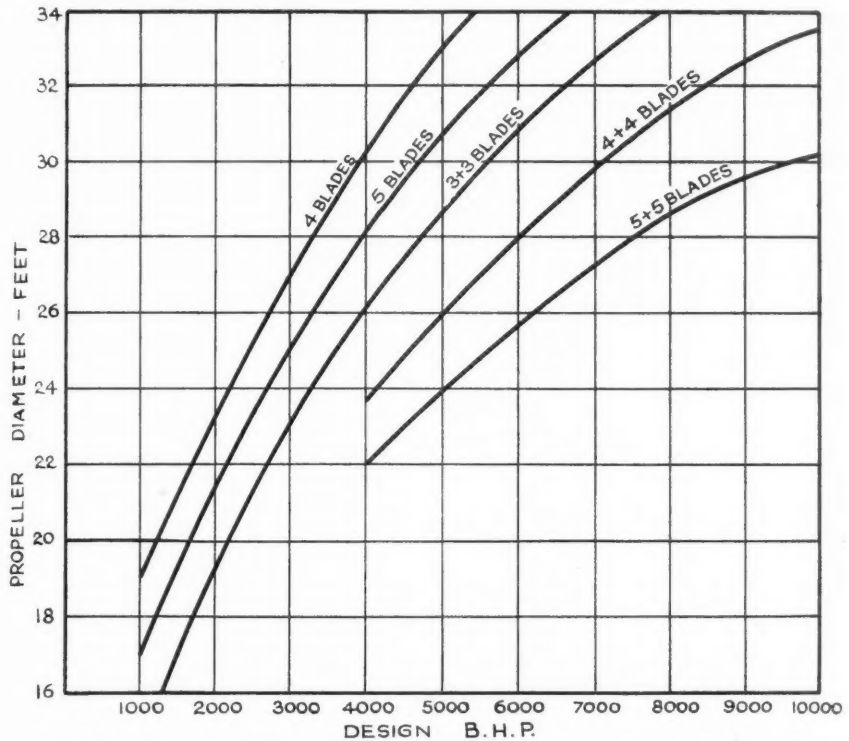



FIG 7 : PROPELLER DIAMETERS FOR TURBINE TYPES AT 300 M.P.H/40000 FT

In estimating the data in Figs. 6, 7, 8, and 9, it has been essential to assume a curve showing the variation of body diameter behind the propeller against horse-power, this being shown in Fig. 10. In each case it is also assumed that the unit is immediately behind the propeller.

The author would welcome the views of the aircraft and engine designers on this curve of

body size, as it is essential in future design work for the propeller industry to have a reasonably accurate knowledge of these body sizes.

The diameters shown on the curves are optimum, but as the curve of optimum diameter for each point is reasonably flat it is possible to employ diameter as much as 10% lower than this without dropping the efficiency at top speed any appreciable amount. Here again these recommended propellers are so far based on mere aerodynamic considerations, as later in the paper the question of their practicability on the grounds of weight, bulk, and controllability are examined.

to the nacelle. Only a small portion of its delivery air is taken by the turbine, the remainder being by-passed directly to the jet.

This system appears to have two main advantages, *viz.*:—

(*a*) A slightly higher envelope efficiency than both propeller and jet systems over a relatively small intermediate speed range.

(*b*) It embraces the possibility of burning fuel freely in the air by-passed from the turbine and thus increasing fairly considerably the power available for short periods, but at an enormous cost in consumption.

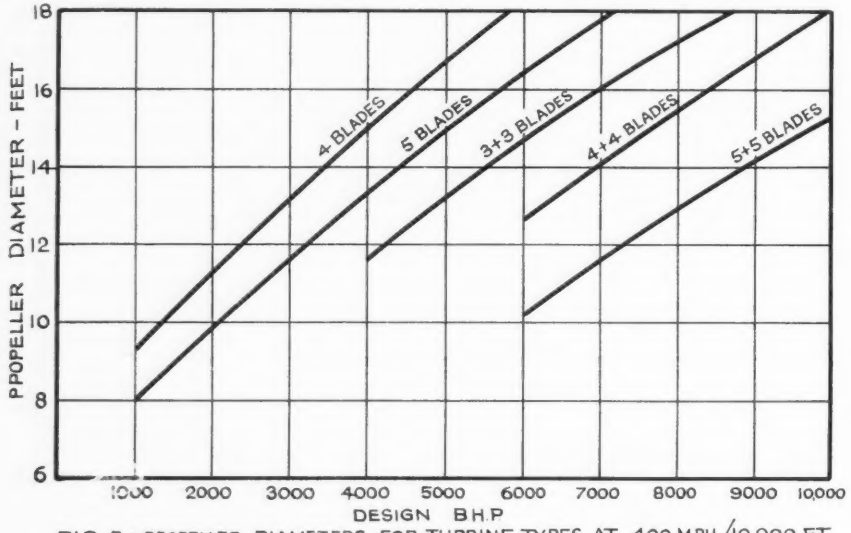



FIG 8 : PROPELLER DIAMETERS FOR TURBINE TYPES AT 400 M.P.H/10,000 FT

## DUCTED FANS.

No treatise on possible future developments of propellers would be complete without examining, broadly, the question of ducted fans. These systems, although not identical with propellers as we know them to-day, are sufficiently similar in purpose and construction to justify the consideration under the general heading of propellers.

The ducted fan system of propulsion, as we understand it to-day, consists of a fairly large diameter ducted fan or axial compressor of relatively low compression ratio at the intake

The disadvantages of the system seem to outweigh these two rather meagre advantages. The main disadvantage is the size of fan and of possible ducts required to deal with the relatively exceptionally large volume of air required. This would appear to complicate the design of suitable aircraft applications by virtue of the large bulk to be disposed, which might well increase the drag sufficiently to nullify any efficiency increase over the jet or propeller system when considering the performance of the aircraft as a whole.

There would appear to be no great problems

to be overcome from the designer's point of view, indeed sufficient work has been carried out on similar axial flow fan installations in the past for various applications to give one confidence in approaching these designs of the future.

There is little doubt that a considerable amount of work will have to be carried out in the future both on design and actual practical test before the relative value of this system of propulsion is definitely established, but it is the author's feeling that the disadvantages will be found to outweigh the advantages and that the ducted fan as such will disappear, leaving the clear-cut problem of propellers versus jet.

The diagram, Fig. 11, shows the estimated propulsive efficiencies of straight jet, gas-turbine/propeller and ducted fan.

## AERODYNAMIC DEVELOPMENT FOR HIGH-SPEED, HIGH-ALTITUDE FLIGHT.

The propeller is the first component of the aircraft to suffer from an approach to the speed of sound, due to its tip speed being a compound of its rotational speed and the forward speed of the aircraft, the compounded figure being usually expressed as the helical tip speed.

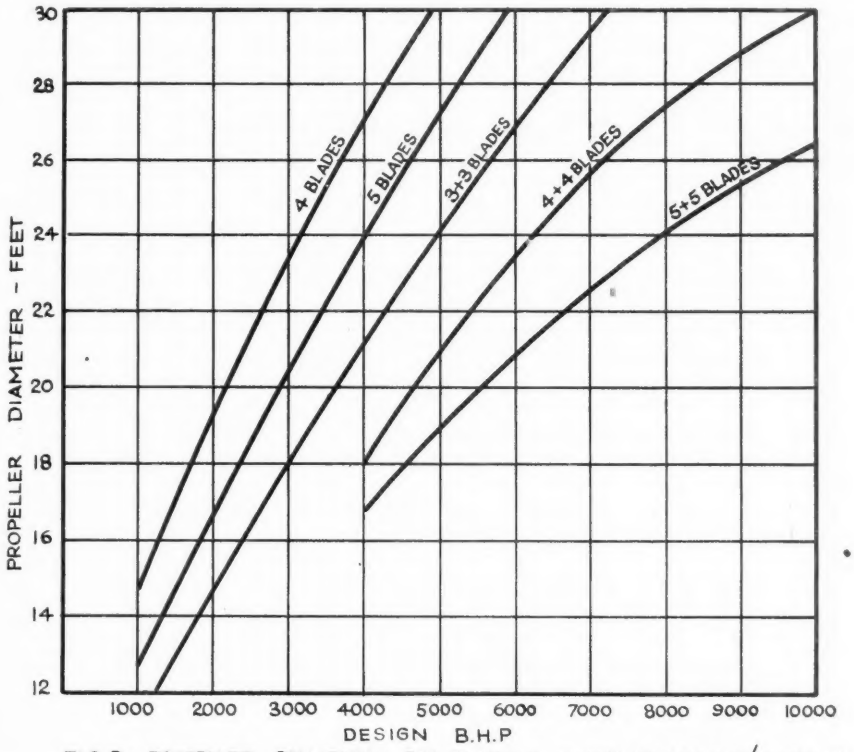



FIG 9 : PROPELLER DIAMETERS FOR TURBINE TYPES AT 400 M.P.H/40000 FT

The following table indicates the increase in the relation between the helical tip speed and the local speed of sound (usually expressed as the Mach No.) on a fighter aircraft starting at 300 m.p.h. and progressing up to 550 m.p.h. at varying altitudes with a constant propeller diameter of 11 ft. :—

| Aircraft speed m.p.h. | Aircraft speed ft./sec. | Propeller rotational tip speed ft./sec. | Propeller helical tip speed ft./sec. | Altitude ft. | Mach No. |
|---|---|---|---|---|---|
| | | | | 10,000 | .79 |
| 300 | 440 | 726 | 880 | 25,000 | .84 |
| | | | | 40,000 | .88 |
| | | | | 10,000 | .86 |
| 400 | 587 | 726 | 932 | 25,000 | .92 |
| | | | | 40,000 | .96 |
| | | | | 10,000 | .91 |
| 450 | 660 | 726 | 982 | 25,000 | .97 |
| | | | | 40,000 | 1.01 |
| | | | | 10,000 | .96 |
| 500 | 733 | 726 | 1034 | 25,000 | 1.02 |
| | | | | 40,000 | 1.07 |
| | | | | 10,000 | 1.01 |
| 550 | 807 | 726 | 1086 | 25,000 | 1.07 |
| | | | | 40,000 | 1.12 |

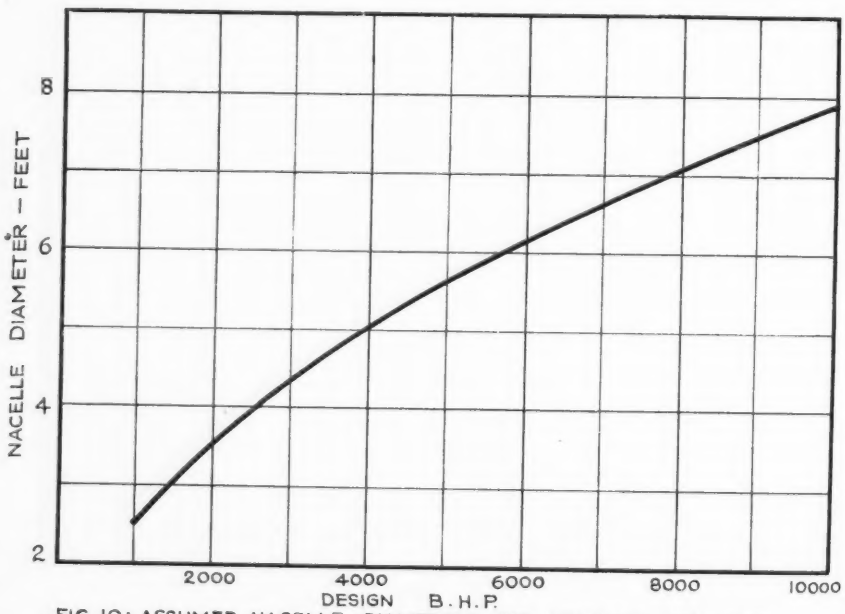



FIG 10: ASSUMED NACELLE DIAMETERS FOR TURBINE ENGINES

The tabulation shows how the Mach No. approaches and becomes greater than unity as the forward speed increases, varying, of course, with altitude.

This increase in Mach No. has forced the propeller designer into improved types of aerofoil sections for high speed aircraft, sections with characteristics such that the speed

at which compressibility losses become very severe is raised. (This condition is expressed as the critical Mach No.) Up to speeds of 400 m.p.h. the type of aerofoil section generally in use is the Clark Y. Between 400 and 450 m.p.h. an intermediate step has been taken by changing from Clark Y outboard of the .85 radius station to an improved section for high speed, wherein the maximum thickness of the aerofoil section is moved backwards to .4 of the chordal width.

As this latter stage could only be a temporary measure, it became essential for speeds beyond 450 m.p.h. to adopt a high speed section over the whole blade length, the type universally used to date being the N.A.C.A. Series 16.

The reason for this may readily be seen from Fig. 12. This figure shows the effect of forward speed on the variation of Mach No. along the blade. In the two cases chosen the same tip Mach No. was maintained by varying the rotational speed, and it is evident that the slope of the curve of Mach No. against radius decreases with increase of forward speed. The third curve on this diagram shows the critical Mach Nos. for the various sections of the blade, and it can be appreciated that for that portion of the blade where the operating Mach No. is in excess of the critical

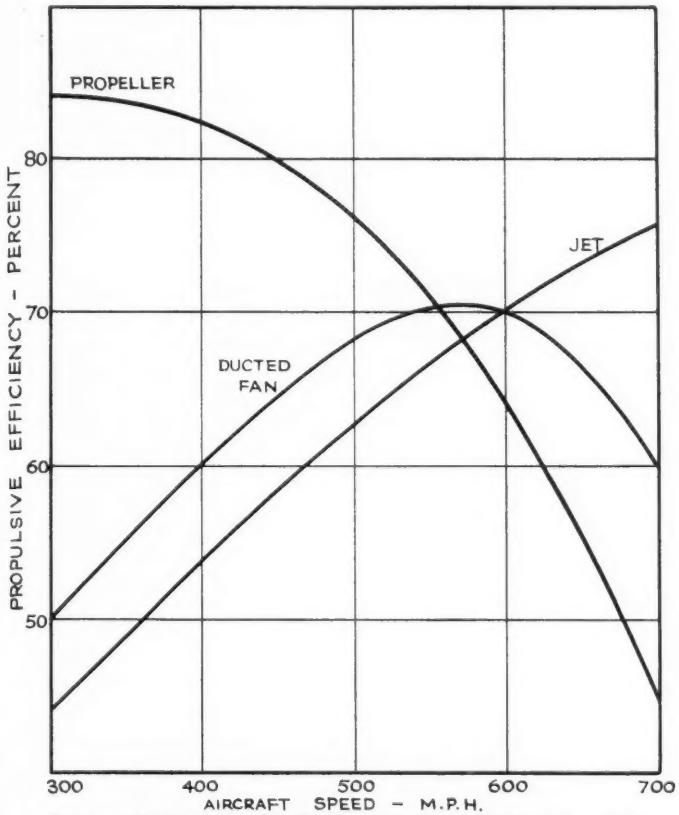



FIG 11 : COMPARISON OF PROPULSIVE EFFICIENCY OF JET, PROPELLER AND DUCTED FAN.

Mach No. compressibility losses will be experienced.

It is very evident from an inspection of the diagram that the compressibility effects spread inwards along the blade towards the root as the forward speed increases, even though the tip Mach No. is kept constant.

It will also be seen from the figure that the compressibility effects spread out from the root with increasing forward speed, and it is for this reason that high speed sections are now being utilized from root to tip of the blade, and much is being done to obtain thinner sections right down to the root.

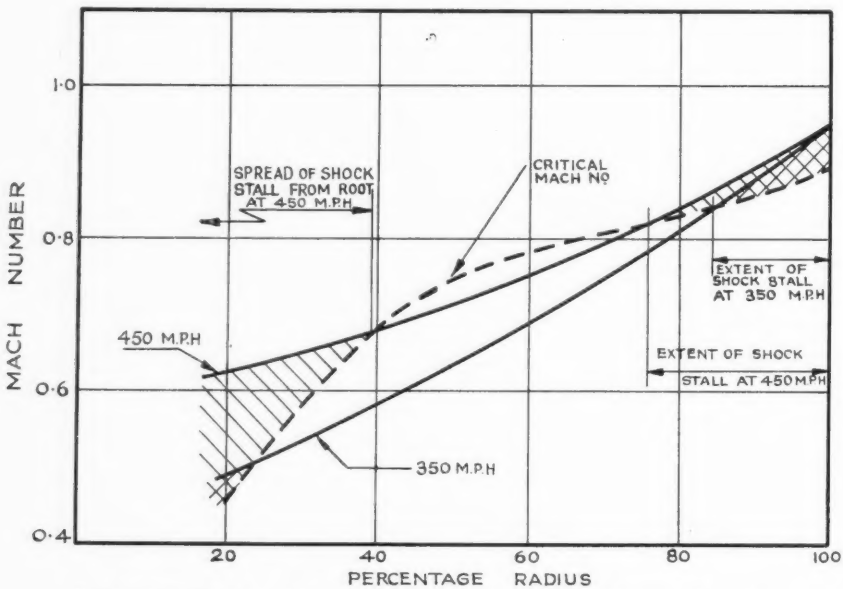



FIG. 12 : EFFECT OF FORWARD SPEED ON COMPRESSIBILITY LOSSES

Between the Clark Y and the N.A.C.A. Series 16 section the critical Mach No. for a typical section of 7% thickness chord grading at a lift coefficient of .3 is raised from .80 to .84.

The sketches in Fig. 13 indicate the difference in shape between the Clark Y and the N.A.C.A. Series 16 sections. It will be seen that on the N.A.C.A. Series 16 the maximum thickness is well back from the leading edge, and the fairing shape employed is such as to give a very sharp leading edge in comparison with Clark Y. There is a stage reached in the Series 16 section where, due to high camber and low thickness/chord ratio, both a hollow under-surface and a slight tendency to reflex at the trailing edge is encountered, but this is associated with high design lift coefficient which, as yet, have not been employed in general use but which may well come to the fore in the future. When sections of the latter type become necessary, manufacturing considerations will arise on the provision of hollow under-surface and reflex trailing edge.

It very soon became evident from full-scale flight testing that while the N.A.C.A. 16 low-lift coefficient blade showed an improvement in top-speed, the climb performance suffered considerably due to the inferior characteristics of the high speed sections at the high operating lift coefficients encountered under climbing conditions.

The climb performance was regained by

considerably increasing the chordal width of the blade throughout its whole length without impairing the top speed.

alternative would be as efficient as the latter, but on pure theoretical grounds a drop in top speed should occur. This combination appears

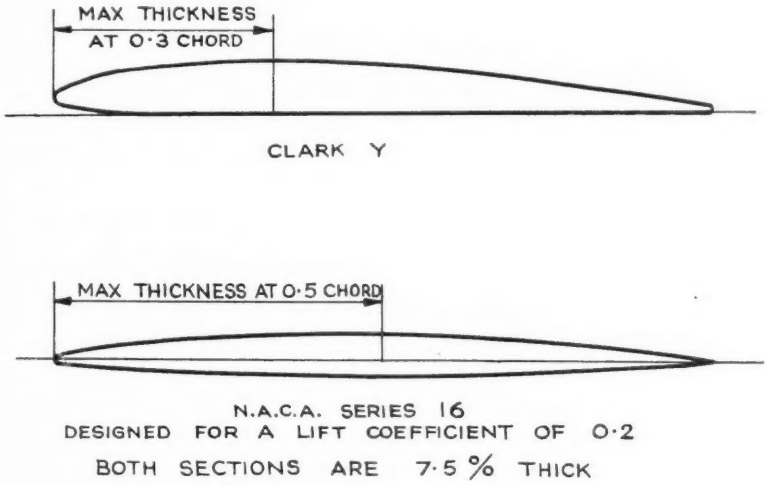

MAX THICKNESS
AT 0·3 CHORD
CLARK Y
MAX THICKNESS AT 0·5 CHORD
N.A.C.A. SERIES 16
DESIGNED FOR A LIFT COEFFICIENT OF 0·2
BOTH SECTIONS ARE 7·5 % THICK

FIG 13: COMPARISON OF AEROFOIL SECTIONS

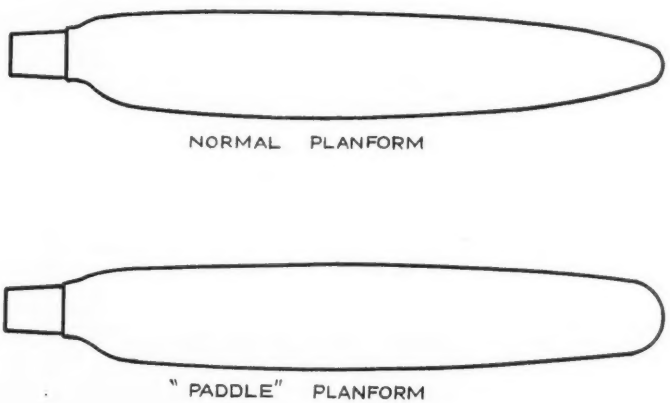



FIG 14: COMPARISON OF PLANFORM SHAPES

An alternative method of regaining the climb would be to use N.A.C.A. 16 sections, but with a high-lift coefficient. The author has no definite data to say whether or not this to have been tried out in America, but so far no definite information of comparative tests is available.

The sketches in Fig. 14 show the difference

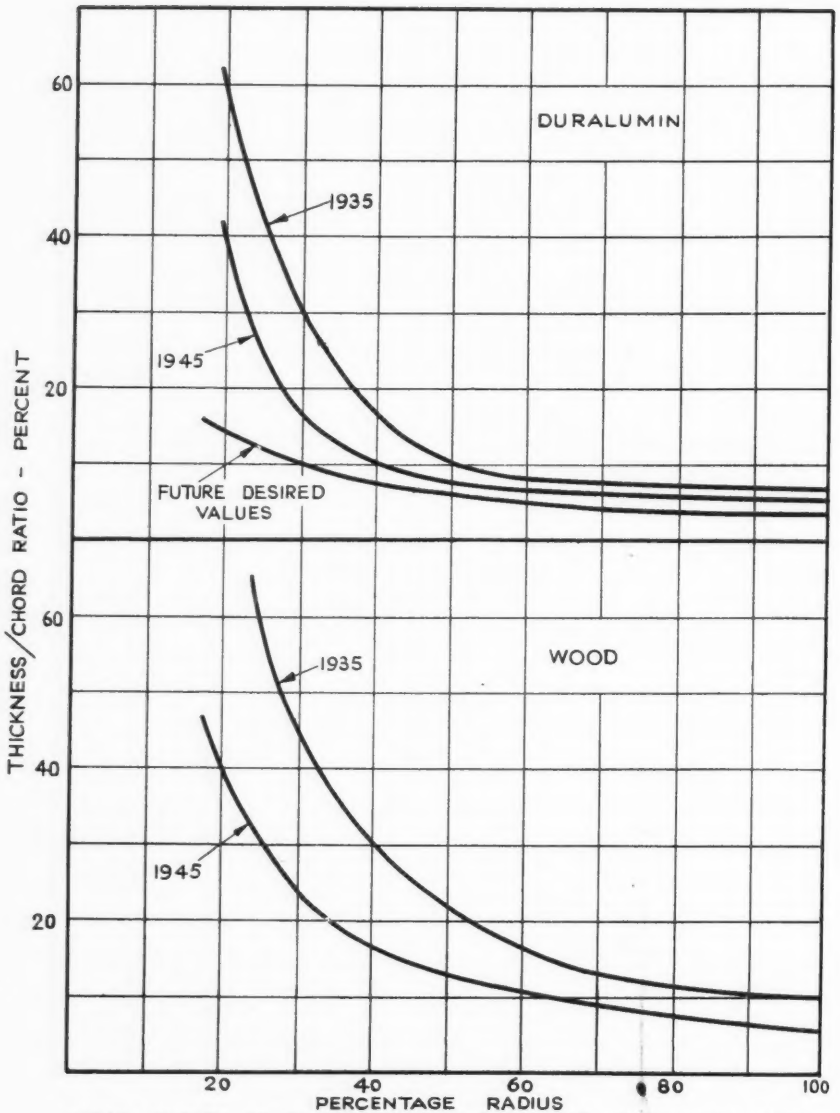



FIG15: CURVES OF THICKNESS/CHORD RATIO FOR DURALUMIN AND WOOD BLADES.

to scale between a normal plan form and a "wide chord" plan form blade.

Another line of attack which subscribes towards improved propeller efficiency at high forward speeds is the development in the reduction of thickness/chord gradings of the blades.

For forward speeds of around 450—500 m.p.h., tip thickness/chord gradings around 5 to 5.5% are generally used. When the forward speed attains the 550 m.p.h. figure, a reduction of this grading to 4.5% will be necessary.

These reductions must, of course, be associated with parallel reductions in the inboard gradings, the attached diagram, Fig. 15, showing the improvements in thicknesses of aerofoils during the war years with a curve showing the objective to which the propeller designer must develop if reasonably high efficiencies are to be obtained on super high-speed aircraft of the future.

Intensive research is proceeding to obtain further advances in high-speed aerofoil design, with particular reference to a type of section which is rather less critical to operating lift coefficient than those tried hitherto, wherein the efficiency falls off very rapidly on either side of the design coefficient. Such improvements in high-speed aerofoil charac-

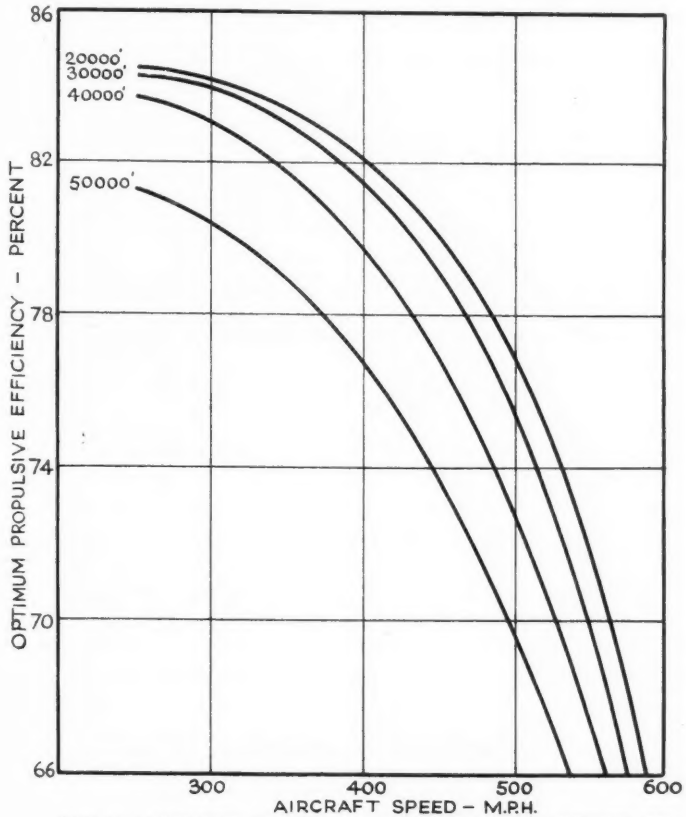



FIG 16 : VARIATION IN OPTIMUM EFFICIENCY WITH ALTITUDE AND FORWARD SPEED OF A SIX BLADE COUNTER ROTATING PROPELLER.

teristics will be essential for aircraft speeds of 550 m.p.h.; the following diagram, Fig. 16, indicating the drop in propeller efficiency as the speed and altitude increase. It can be seen that the efficiency starts falling off rapidly beyond 400 m.p.h., and at 550 m.p.h. it has dropped as low as 65%.

## TWO SPEED GEARS.

Referring back to the tabulation under the case of the 550 m.p.h. condition between 25,000 and 40,000 ft., a two-speed gear can be made which will reduce the tip Mach No. for top speed flight to a figure in the region of .95 to .97 which is that commonly used in normal design.

The application of the two-speed gear to heavy classes of aircraft such as bombers and commercial aircraft is not by any means as pronounced as in the fighter class, since in the

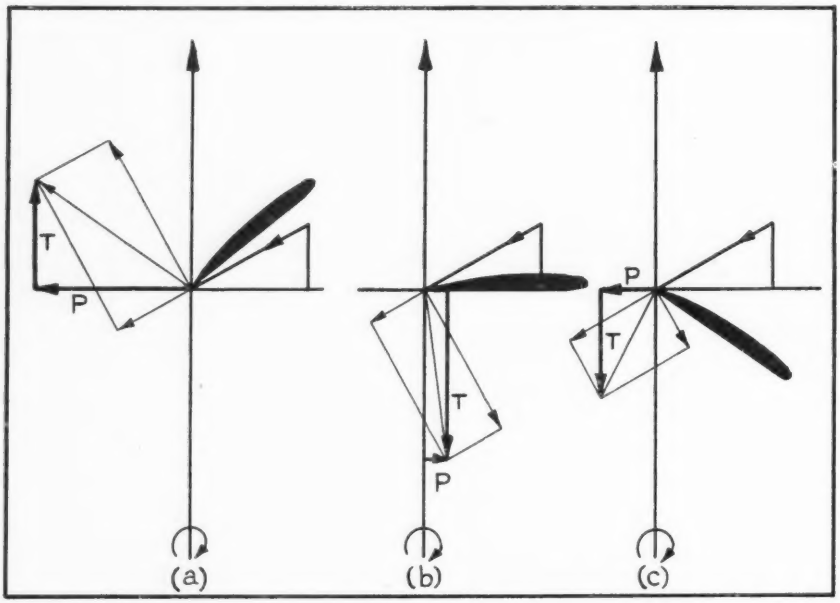



FIG 17: OPERATION OF BRAKING PROPELLERS
(a) NORMAL FORWARD THRUST
(b) WINDMILLING BRAKE
(c) POWER-ON BRAKE

aerodynamic development, it can be observed that the tip Mach Nos. of greater than unity occur from 500 m.p.h. upwards. Such conditions in the supersonic region introduce the need for a two-speed gear drive to the propeller, in order to reduce the tip Mach No. at top speed by use of a relatively low gear ratio, and still have available a second ratio of a high value for take-off and climb. In the former aircraft ample propeller diameter is usually afforded and the top speeds are such that the Mach Nos. never approach the figures of the fighter aircraft.

The two-speed gear considerably extends the use of the propeller as a means of aircraft propulsion, by permitting its use at higher speeds without jeopardizing the take-off and climb performance.

## PROPELLER BLADE MATERIALS.

Having examined the requirements of high forward speeds at high altitudes, and the demand for thinner aerofoil sections of improved shapes, this immediately introduces the question of blade material.

Three materials have been used throughout the war, namely, duralumin, compressed wood and hollow steel, the latter being wholly associated with certain types of American propellers. The use of duralumin has been universally applied since the introduction of the early ground adjustable pitch propellers, the experience from which proved very valuable in its subsequent adoption for the variable pitch type.

The compressed wood blade, initially developed in Germany, was taken up previous to the war, and concentrated upon in a serious manner in this country in early stages after the outbreak of hostilities when duralumin was in very limited supply. It is not by any means overstating the value of the compressed wood blade in claiming that this foresight "saved the day" without having to accept any reduction in operating efficiency up to 450 m.p.h. Further, its feature of being capable of quick repair has further enhanced its value throughout the war years.

It is now apparent that for speeds in excess of 450 m.p.h., demanding, as pointed out above, new forms of finer sections, manufactured to closer tolerances in the interest of maintaining efficiency, this blade must give way to a metal blade where the section requirements can be more readily met on a practical basis. The author foresees the use of duralumin still continuing where the wood blade leaves off for the high speed fighter case, followed possibly by hollow steel or even solid steel blades.

Providing a clean design of root cuff is developed the hollow steel blade should go a long way towards achieving improved sections of thinner gradings, but the attempts at cuffs so far achieved fall considerably below the standard of requirement for high speeds.

The solid steel blade offers excellent possibilities of super thin sections combined with the best qualities of durability.

The question of the relative capabilities of these blades to withstand the alternating vibratory stresses imposed from the engine torsionals are discussed later in the paper, as also is their relative weights.

On the heavier classes of aircraft in the bomber and commercial range, there is little doubt that the hollow steel blade will be the objective on the grounds of durability and weight in the larger propeller sizes.

The wood blade is still maintaining its popularity on the grounds of reduced weight on certain commercial aircraft for the immediate post-war period, and its continuance is a matter of weighing up the economies of the aircraft operation by comparing the saving in £ s. d. by increasing the payload, against the more frequent blade replacements necessary on durability grounds against duralumin or hollow steel.

## SINGLE-HUB PROPELLER LIMITATIONS.

The maximum number of blades so far used in a single hub is five, and would appear to be the limit on both aerodynamic and mechanical grounds.

The aerodynamic limitation is mainly due to the heavy swing at take-off which occurs in the 2,500 h.p. high-speed fighter, it becoming more and more difficult to handle the machine. It has been shown in practice that the use of high take-off boosts is limited on this class of aircraft on this account. An aircraft operating from a fleet carrier suffers more than any other type on account of the restricted landing platform, together with the allied difficulties due to roll, etc.

This is accounted for by the temptation to absorb high powers by increasing the number of blades in a single hub which, although it reduces the loading per blade to within reasonable limits, still does not overcome the high disc loading present.

A further aerodynamic limitation occurs in a turbine propeller installation with an air

entry duct annular to the propeller. The presence of five blade roots rotating in one direction in front of the duct may cause a reduction in efficiency due to the presence of swirl and turbulence behind the blade roots.

The mechanical limitation consists of the difficulties arising in keeping down to a minimum the height of the hub socket so as to keep it wholly inside the spinner, and also to provide an efficient blade aerofoil shape at the spinner periphery. This difficulty is still more pronounced on turbine propellers where the spinner diameter in front of the air duct is considerably smaller than the piston engine spinner, demanding a propeller hub with the absolute minimum height of blade socket.

## COUNTER-ROTATING PROPELLERS

The aerodynamic attributes of counter-rotating propellers are generally well known, and intensive flight testing carried out over the past two to three years has confirmed the various claims. Also, this endurance testing has given ample opportunity of progressively improving the actuating mechanism and today the propeller can be said to be mechanically sound.

The number of blades so far used has been a maximum of six (3+3) but no difficulties are foreseen either aerodynamically or structurally in increasing the number to eight (4+4) or ten (5+5).

*The spacing between the two halves.* Tunnel tests carried out on counter-rotation have indicated that a spacing of between one-eighth and one-sixth of the propeller diameter is desirable from considerations of efficiency and vibration. Further investigation into this point is desirable before any hard and fast rules can be laid down.

*Relative rotational speeds of the two halves.* Tunnel tests indicated that if the two propellers were not of equal diameter and running at equal rotational speeds there is a tendency to excite blade vibrations, and hence cause a reduction in efficiency. The equal rotational speeds are further desirable in order to maintain the "white lines" (caused by stroboscopic effect of the blades passing one another) stationary. With unequal speeds these lines rotate slowly in the plane of rotation of the propellers and have been proved to be very tiring to the pilot.

*Aircraft fin effect.* Early flight testing of the counter-rotating propeller showed a tendency for directional instability of the aircraft caused by the high solidity propeller acting as a fin forward of the C.G. of the aircraft. This trouble was overcome by increasing the fin area which negatived the effect from the propeller, the degree of increase in area being of the order of 15 to 20%.

*Relative pitch angle setting of the two halves.* It has been shown by fairly extensive wind tunnel tests that the most efficient counter-rotating combination is that in which equal torques are absorbed by both front and rear halves. In order to achieve this it is necessary to operate the rear half at a slightly finer pitch setting than the front, due to the different inflow to the rear half occurring from the presence of the front component. Although it seems to have been thought necessary in the U.S.A. to vary this difference linearly with the pitch angle of the front half, we have found in this country no justification for this complication, and British practice is to index the rear blades a definite amount finer than the front and maintain this difference throughout the range of the propeller. The degree of difference is of the order of $1\frac{1}{2}^{\circ}$ for equal rotational speeds.

It should here be stated that, while the equal distribution of torque is sensitive to small changes in this difference in pitch setting, the overall efficiency of the propeller is not, and on present-day counter-rotating propellers this figure could be varied by as much as $2^{\circ}$ without affecting the performance noticeably. It is felt, however, that on future very high speed applications with heavily loaded propellers this difference in pitch setting will become more critical from the point of view of performance.

*Improvement in performance.* Up to the present the counter-rotating propeller has

shown little or no improvement in performance at top speed, although a very definite improvement in performance has been evident under highly loaded conditions of take-off and climb. As forward speeds increase, however, *i.e.*, of the order of 450 m.p.h. upwards, it is necessary to limit the rotational tip speed more and more in order to keep the tip Mach No. within reasonable limits. The top speed case will therefore become more and more highly loaded and we can then hope to see a useful advantage of the counter-rotating propeller at top speed, due to its ability to reclaim the rotational energy losses associated with heavily-loaded propellers.

*Elimination of swing.* The entire elimination of swing with the counter-rotating propeller makes it not only attractive for ease of aircraft handling but an absolute essential for aircraft of the deck landing type. Further, the elimination of swing enables high boosts at take-off to be used right up to their aerodynamic efficiency limit, again a very big advantage on deck aircraft.

No propeller-driven aircraft specification of the deck landing type should ever again be issued to the industry without an insistence on the use of counter-rotating propellers.

*Turbine application.* The application of the counter-rotating propeller as a type for the turbine engine, will no doubt become universal. Firstly it enables a reduction in diameter to be obtained by multi-blading and hence assists undercarriage design and, secondly, should be a considerable improvement over the single hub type, because the reduction in swirl and turbulence is considerable and as such improves the conditions of airflow around the air entry duct into the unit.

## CO-AXIAL PROPELLERS

The term "co-axial" propellers is intended to differentiate between the counter-rotating type wherein the whole engine power is absorbed by both halves, and the type in which each half of the propeller is driven by an independent engine. The two halves still rotate in opposite directions. One reason for adopting the co-axial type is to improve the safety of the aircraft, since in the event of the failure of one engine unit it will still be possible to continue flight with the other unit, driving as it does its own half of the propeller. In this case the particular half-propeller allied to the "dud" engine will be feathered.

A further advantage of this arrangement, associated with buried engines, is that two power units can be used, linked in such a manner as to present only one propeller unit at the leading or trailing edge of the wing according to the arrangement.

The main problems which arise in a propeller of this type consist firstly of the effect on efficiency of the operating half when it has a stationary feathered propeller either in front or behind. Tunnel tests have shown that when operating the front half of the propeller at a blade angle of 45° in front of a propeller feathered at 83°, the drop in overall efficiency of the whole unit is 5%, but for finer front blade settings this loss decreases fairly rapidly. This drop in efficiency is wholly caused by the drag of the feathered half, and it does not appear that the efficiency of the front half alone is affected by the presence of the feathered propeller behind it. It should be appreciated that the angle of 45° is rather higher than would be expected on an installation of this type used in a commercial aircraft at a cruising speed of around 300 m.p.h. This condition on a co-axial propeller is, therefore, no worse than the effect on a normal multi-engined installation.

The same effect is produced with a feathered "front half" and an operating rear half.

A further problem which arises with the co-axial propeller is the sensitivity of the blade angle required for feathering one half in the presence of the other half rotating in front or behind. Tunnel tests indicate the feathering angle to vary according to the condition of operation of the other half, causing a slow rotation in either direction.

The slight residual torque causing this rotation can be easily dealt with by the pro-

vision of a small brake either situate on the propeller or on the driving shafts from the submerged engines. It would appear to be essential that this brake be in such a position that it can be operated and controlled entirely by the flight mechanic who may be executing a repair to the "dud" engine, as it is he alone who must have full say in this respect.

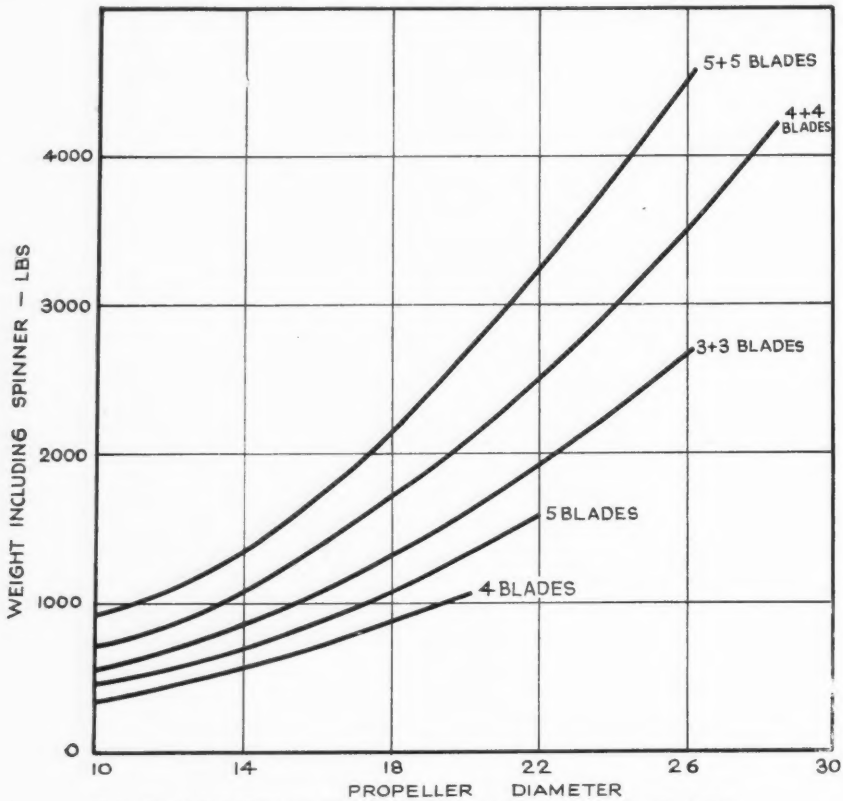



FIG 18: WEIGHTS OF PROPELLERS HAVING DURAL BLADES

## PROPELLER NOISE.

During the war years there has been little necessity to study very deeply the noise level caused by the various units of the aircraft, *i.e.*, as to whether the aircraft, engine or propeller noise predominate.

With the serious attention being given to commercial aircraft the reduction in noise level is of high importance, and it is, therefore, the duty of the propeller designer to make a close study of the extent to which his component is responsible and to establish the source of the propeller noise.

Research into this feature will demand specialized equipment and personnel who can devote the whole of their time to this subject in order to produce the maximum amount of data on propeller noise in good time to enable it to be employed on current designs.

It is equally important that the aircraft and engine manufacturers should carry out parallel investigations, in order that a clear understanding can be arrived at and a concerted effort made by all concerned to reduce the total noise level.

PROPELLER WEIGHTS.

The diagrams, Figs. 18 and 19, show the broad forecast of propeller weights anticipated within the next five years.

Since the future design of propeller hub mechanism will be a complete break-away from present practice, these weights have been prepared in a broad sense and individually may be modified according to the final designs. But, since by far the major portion of the weight comprises blades alone, changes in hub mechanism, while having a slight effect, will not unduly alter the trend.

The diagrams shown cover propellers fitted with duralumin and compressed wood blade only, and are based on piston engine data. There is no doubt that on turbine engines with the reduced vibration the duralumin blade will compare more favourably on account of the smoother unit permitting thinner blades and smaller root sections than hitherto.

From the data available in this country, it is very difficult to compare a range of hollow steel-bladed propeller weights, since advantage can be taken of the smaller root afforded with this type, and hence more is involved than merely comparing blade against blade. From approximations it is fairly safe to say that the hollow steel propeller should come out considerably lighter than its duralumin counterpart for diameters of 15 ft. upwards, although here again this will be of a different degree for turbine engines.

It would appear, however, that the hollow steel bladed propeller throughout a complete

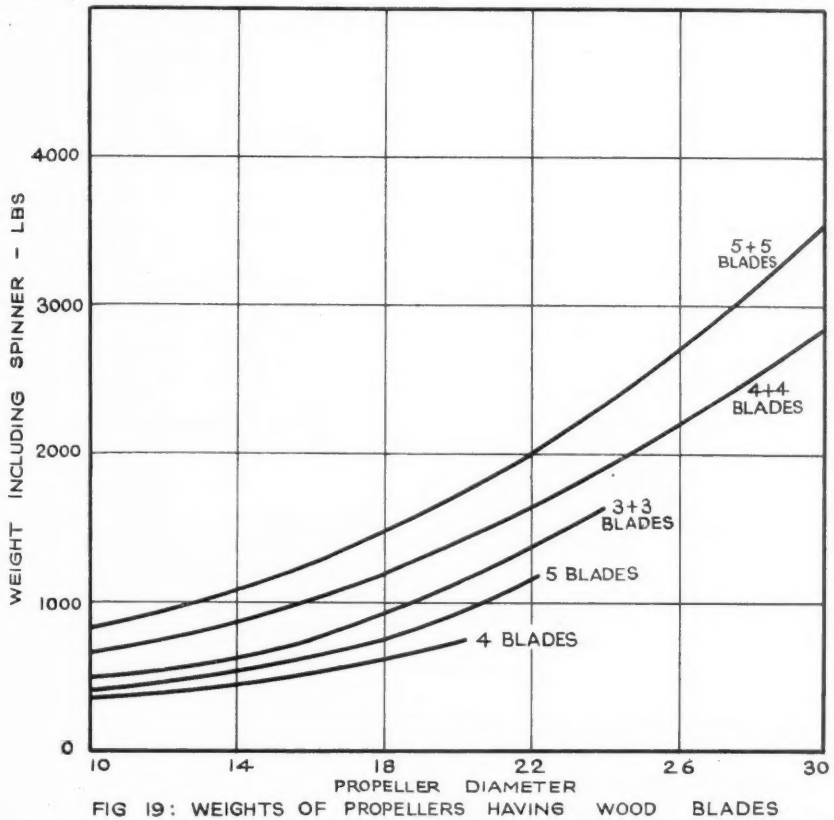



FIG 19: WEIGHTS OF PROPELLERS HAVING WOOD BLADES

range would still come out heavier than the compressed-wood bladed propeller.

For the same reason no comparison can be given of the relative weights of a solid steel bladed propeller, but an estimation made on an experimental propeller indicates that for a five-blade Spitfire propeller there is very little difference in the overall weights between this type and its duralumin counterpart.

Taking several instances from the diagrams Figs. 18 and 19, it can be seen that the weight of a ten-blade counter-rotating propeller for a 4,000 h.p. piston engine developed at 40,000 ft. at a forward speed of 550 m.p.h. would come out at 1,500 lb. for duralumin blades, and 1,170 lb. for wood blades.

For a 16 ft. diameter ten-bladed propeller for 10,000 h.p. piston engine at 10,000 ft. and 300 m.p.h. the weight of the propeller would come out at 1,700 lb. for duralumin blades and 1,250 lb. for wood blades.

For a 27 ft. diameter ten-bladed propeller for 10,000 h.p. piston engine at 40,000 ft. and 300 m.p.h., the weight of the propeller would come out at 4,800 lb. for duralumin blades, and 2,900 lb. for wood blades.

In each of these cases, as previously pointed out, the duralumin bladed propeller would, for an equivalent turbine installation, come out more favourably.

Figs. 20 and 21 have been prepared to show diagrammatically the order of the weights of duralumin and wood bladed propellers in pictorial form to serve as an approximate "ready reckoner." Here again, if turbine units replace the piston engine type beyond 5,000 h.p. the weights will be on the high side, but should serve as a guide until data of a more definite nature is available on actual reductions possible on turbine propeller weights.

## PROPELLER DE-ICING.

The problem of aircraft de-icing has had a relatively slow development, by far the greater amount of work having been done in America and Canada where natural icing conditions for testing are more frequent than in this country. The operational experiences of day and night bombing throughout the war have shown the necessity for urging this development.

Particular stress is placed on the importance of efficient de-icing of the propeller on account of the reduction in propulsive efficiency and vibration which ensues with ice accretion on the propeller blades.

The development of de-icing of the propellers has been a lengthy affair because the prevention or removal of ice from the propeller blades can only be done by actual flight testing. The most satisfactory results are obtained by testing under natural conditions, but these can be rarely lined up with the actual testing both from the aspect of place and time and the extent desired.

It has been necessary, therefore, to carry out the testing by producing ice on the blades artificially by means of a water spray contained in an outrigger mounted on the aircraft fuselage and spraying rearwards into the propellor.

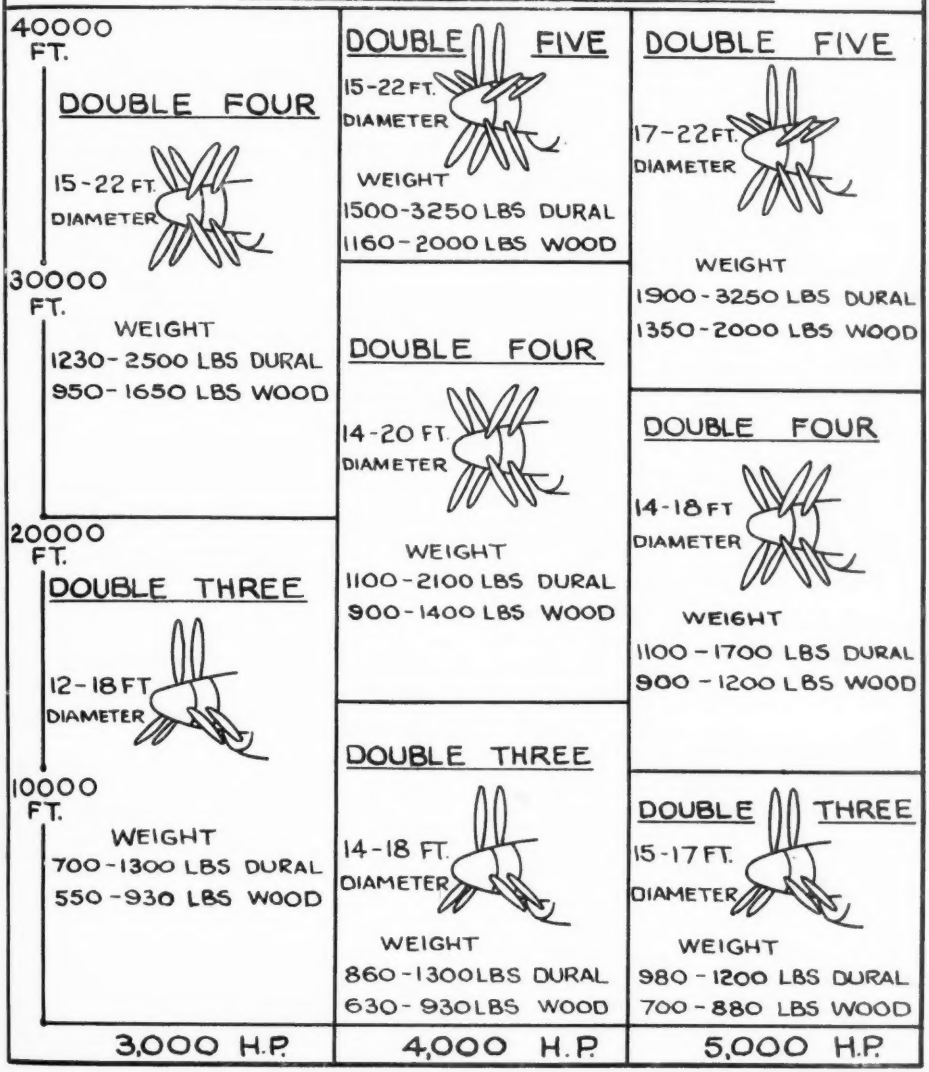
The methods so far utilized come under two categories:—

Complete prevention of ice formation.
Temporary prevention.

In the first category the thermal method has been developed consisting of heating a resistance element fitted to the leading edge of the blades by means of a propeller driven alternator in which the electric power for the de-icing, approximately 250 watts per blade, is provided by the alternator. The only drain on the aircraft batteries is of around 90 watts required to excite the stationary coils in the alternator. Considerable development has been carried out on this method, and it may eventually be the universal scheme adopted, with possibly a separate alternator mounted and driven on the engine feeding the current to the blade elements via slip rings.

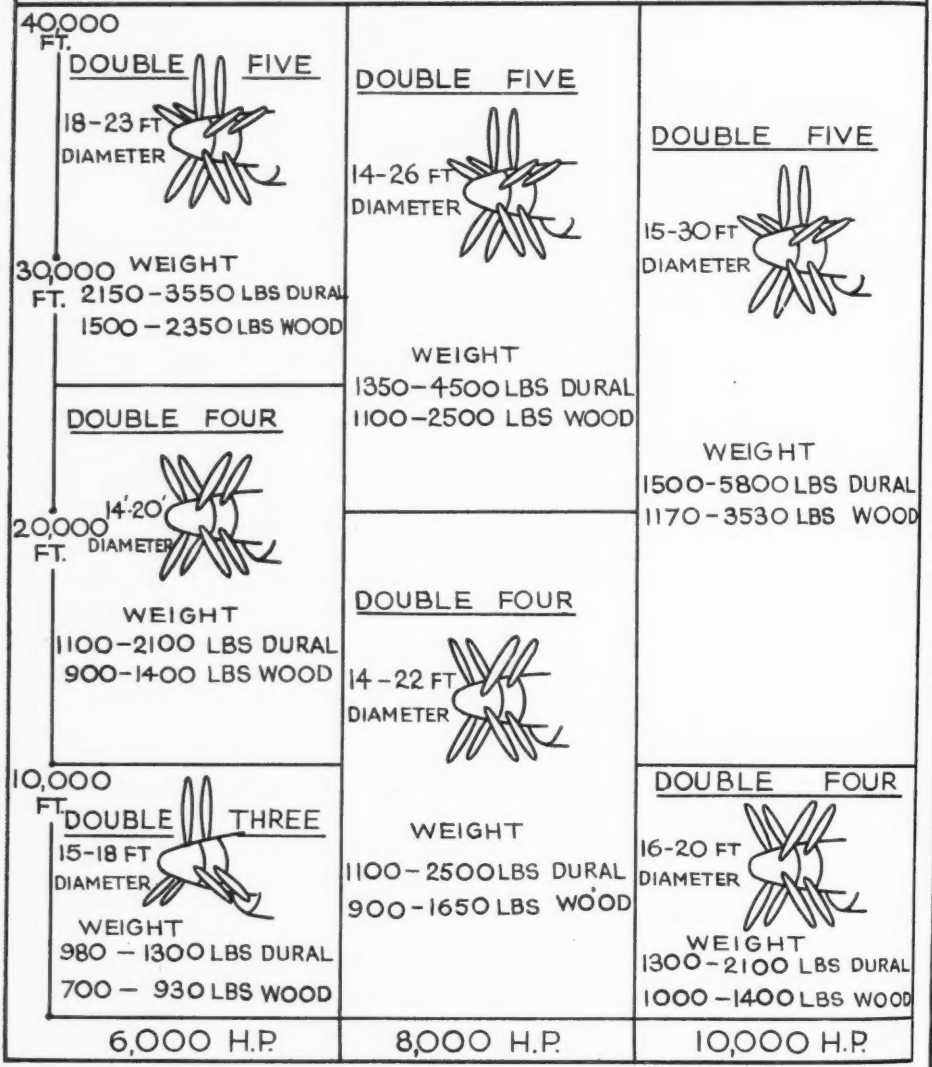
The other thermal method is the use of exhaust heat applied mainly to the hollow steel blade, using the hollow feature as a means of transmitting the heat internally along the blade length.

FIG 20 PICTORIAL ANALYSIS OF FUTURE PROPELLER TYPES 3000 H.P. — 5000 H.P.




In the second category temporary prevention has been effected by the fluid method being collected from an electric metering pump into a slinger ring mounted on the propeller hub and the fluid forced outwards by centrifugal force through pipes, the nozzle of which is fitted close to the leading edge of the blade. This system is very sensitive to the position of the nozzle relative to the leading edge, and considerable care has to be taken in preventing damage or any displacement of the nozzle when handling the propeller. The

FIG 21 PICTORIAL ANALYSIS OF FUTURE PROPELLER TYPES
5,000 – 10,000 H.P.




system using a mixture of alcohol and glycerine has had a reasonable degree of success, and providing great care is taken in the maintenance it de-ices considerably well.

The other temporary prevention method is the use of de-icing pastes which are applied to the blades prior to each flight, and which has been used considerably on heavy bombers throughout the war. It remains, however, that the paste method is only an expediency

as the cleaning of each blade prior to flight and re-covering with paste make too great a demand on the maintenance personnel.

Further development is necessary on the thermal and liquid systems to determine, *viz.*:—

(*a*) The effect of ice on propelier efficiency.

(*b*) The effect of the de-icing agent on propeller efficiency, *i.e.*, irrespective of ice formation.

(*c*) The most satisfactory means of ice prevention, whether thermal or liquid.

There is no doubt whatsoever that on future multi-engined aircraft of either the bomber or commercial types efficient propeller de-icing will rank as one of the most important safety features of the aircraft.

## BRAKING PROPELLERS.

Over the past two years considerable development has been carried out on the utilization of the negative thrust from the propellers as an aircraft brake.

*Aerodynamic considerations.* In order to make clear the operation of such a propeller recourse is made to the simple blade element theory, and the three sketches in the diagram, Fig. 17, a, b and c, show the operation of the propeller under braking conditions.

In Fig. 17a, it can be seen that in normal flight the resolution of the resultant force on the blade element gives a thrust "T" forward and an anti-rotational force "P" to the left, this direction being considered positive for a normal driving power unit.

In Fig. 17b, the blade element is given a small negative incidence resulting in a higher negative lift and fairly low drag. The resolution of the resultant force here gives a thrust "T" and an anti-rotational force "P" both negative. This means that the force acting in the plane of the propeller is tending to turn the engine, and this condition is, therefore, a windmilling one where no engine power is necessary.

In Fig. 17c, the blade element incidence is reduced still further until it has a fairly high negative value. Here it can be seen that due to the low value of lift and very high drag the resolution of the resultant force produces a negative thrust "T," but a positive anti-rotational force "P." This case, therefore, needs engine power to rotate the propeller and produce negative thrust and is, therefore, referred to as the power-on condition of braking.

*Design problems.* The two major problems which confront the propeller designer on braking propellers are, firstly, the requirement for very high rates of pitch change of the order of 40°—50° per second, so that no serious over-speeding of the engine will occur when the blades are passing through the minimum torque position. Secondly, the negative thrusts utilized induce higher blade root stresses than occur with the normal driving thrusts, and to keep these stresses inside permissible limits careful consideration in the blade design is essential.

On the question of the use of windmilling dive brakes in general, the propeller designer would welcome the views of the aircraft designer as to how he intends to use the propeller brake. There seems to be a feeling in the aircraft industry that the propeller designer can cater for a windmilling dive brake for use at any forward speed. It is essential that some compromise speed be laid down for each application, as otherwise propellers can become so cumbersome and heavy as to be inefficient at what, after all, is their primary function—forward propulsion.

In catering for extremely high speed use the propeller blades, blade roots and consequently propeller hub, will have to be increased in size a considerable amount in order to deal with the extremely high loads involved, in addition to which the rates of pitch change may have to be increased still further to avoid the possibility of engine overspeeding.

It appears to the author that the most satisfactory general method of application of

the windmilling dive brake, in order to achieve this compromise, would be to commence the braking cycle at a relatively low speed of, say, 300 m.p.h. A.S.I. and then allow the machine to accelerate in a dive up to equilibrium speed, rather than to commence the dive and apply the dive brake when something like terminal velocity is reached.

*Applications.* The uses to which braking propellers can be put consist of:—

(*a*) Dive bomber brake.

(*b*) Float brake for deck landing.

(*c*) Landing brake.

(*d*) Flying boat manœuvrability.

*The dive bomber braking propeller* has so far been developed on the windmilling principle. With a machine of 15,000 lb. all-up weight a negative thrust in a dive of 10,000 lb. is possible at a speed of 290 knots A.S.I. A very considerable steepening of the diving angle has been achieved, and the effects on the aircraft controls of the altered slip stream are negligible. This application of the braking propeller affords considerable easement in the design of diving flaps.

The use of power-on braking on this application would give higher negative thrusts and much thought is being directed along these lines, but two important problems arise. Firstly, due to requirements of simplicity of control, the propeller when in the braking condition operates in fixed pitch. If power-on braking is used constant speeding in the braking position would be necessary in order to keep the propeller under control at the high forward speeds. Such a condition would necessitate a more complicated system of operation, wherein some scheme for reversing the oil feeds would be required when the blades have passed through the minimum torque position. Secondly, it has been established that with the windmilling propeller the changed air-flow over the aircraft does not impair the handling characteristics, but there seems to be some grounds for the belief that under power-on braking conditions at high speeds the air-flow may be so bad as to make the machine very difficult to control.

*Float brake for deck landing.* Although little or no experience is available on this application the power-on braking feature could be applied to reduce the "float" period when coming in to land, *i.e.*, to steepen the angle of glide very considerably just prior to touch-down. Full scale testing alone will show the value of this feature, as it is feared that a serious decrease in the effectiveness of both rudder and elevator may occur when under the braking condition.

*Landing brake.* This application is used to reduce the landing run of heavy machines after touch-down by using the power-on brake, wherein full take-off power is applied at maximum engine speed with the blades in a negative pitch of around 25°. A reduction in landing run of approximately one half of the normal has been achieved with considerable reduction in landing wheel tyre wear.

*Flying-boat manœuvrability.* This application has been in operation for some considerable time, and uses the power-on type, producing a negative thrust at static or low-speed conditions, thus permitting considerably better manœuvrability on the water.

*Braking propellers on Turbine engines.* With the generally cleaner aircraft lines associated with turbine installations and also the use of tricycle undercarriages, the braking propeller should be of considerable value either as a landing brake or a dive bomber brake.

The propeller designer will require to know the power required to motor the turbo-compressor system with throttle closed, as this is likely to be rather higher than the piston engine under this condition, and may result in lower rotational speeds under windmilling conditions. In the case of a separate turbine driving the propeller this motoring power will be lower than the piston engine, giving rise to higher windmilling speeds.

It seems very likely from the foregoing that it is essential to record very closely the throttle shut motoring powers of turbines to

arrive at some condition which will ensure reasonable rotational speeds for windmilling braking applications.

## VIBRATION PROBLEMS.

Vibration problems in the propeller consist mainly of those created by propeller unbalance, engine excitation and installation. Dealing firstly with vibration due to propeller unbalance the various forms are as follows:—

Static unbalance.
Dynamic unbalance.
Aerodynamic unbalance.
Aerodynamic excitation due to blades passing obstacles or turbulent airflow.
Engine and installation excitation.
Reactionless modes.

Dealing briefly with each in turn:—

*Static unbalance* does not present any problems, since propeller blades are individually balanced and the complete propeller assembly finally balanced to within three inch-ounces.

*Dynamic unbalance.* Correction for this form of unbalance, due to unequal distribution of masses in the propeller, can only be determined by spinning the complete propeller. To carry out such a form of balancing on a production basis, especially during war time, is rather difficult, and by statically balancing at various angles a certain amount of dynamic out-of-balance is corrected. Equipment has been set up both in this country and in America for dynamic balancing, but has never been used universally.

It will, no doubt, become necessary to treat this form of unbalance more seriously for future propeller applications, particularly on commercial passenger carrying aircraft, and specialized recording instruments are under development which enable the correction to be carried out on the actual aircraft.

*Aerodynamic unbalance.* This form of unbalance is due to the individual blades in the propeller giving unequal thrusts or absorbing unequal torques on account of the variations between blades which can occur as a result of manufacturing dimensional tolerances. Correction for the thrust unbalance has received very serious consideration in this country, and machines have been designed and made on which the correction in terms of a final differential fine pitch angle can be carried out on a production basis.

The introduction of this form of balance has, without any doubt, played a most important part during the war, being firstly applied to high powered high-speed fighters, and more recently to the heavier classes of aircraft. Its advantages have been fully recognized by the American propeller industry and here again has removed a vibration problem which at one time was assuming very serious aspects. Continuation of this form of correction will be an essential feature for propellers of the future.

On certain installations it has been shown that the torque unbalance is more serious than the thrust, and by using the same machine as designed for thrust balance correction it has been possible to meet the torque correction on a production basis also. It is, of course, impossible to achieve both thrust and torque balance together by a single differential blade angle setting, but it is possible to overcome the more serious, or possibly to effect a compromise if necessary.

*Aerodynamic excitation.* The main trouble experienced with this form of unbalance occurs due to the blades passing close to some protruberance such as fuselage or air intakes, etc. Very little short of drastic action can be done to remove this unbalance, such as altering the relative positions of the propeller and the protruberance, or changing the number of blades in the propeller in order to alter the frequency of the vibration from a resonant value.

It is essential in an unbalance of this type that consideration be given in the early stages of the aircraft design to prevent such a form of unbalance arising.

*Engine and installation excitation.* The sources of vibration arising from this source can cause high alternating stresses in the propeller hub and blades. The two main sources

are the effects of torsional oscillations of the engine crankshaft and axial vibration (fore and aft) of the engine.

In addition to the engine torsional vibration effects, vibration studies in the propeller are beginning to show an increase in vibratory stresses due to a whirl of the complete engine installation. In this form of vibration a point on the propeller shaft describes an orbit, the motion of which can be either in the same direction or alternatively in the opposite direction of the propeller rotation.

*Reactionless modes of vibration.* This form of vibration is aerodynamically excited and can occur with four or more blades in a single propeller, but not in a three-bladed propeller. It has the peculiarity that the blades vibrate in such a manner that there is no reaction present at the propeller shaft tending to displace the shaft either laterally or torsionally. Since this form of vibration is contained entirely in the propeller itself, no advantage can, therefore, be taken of any inherent damping or energy dissipation which may be present in the engine system. Experience so far has shown this form of vibration to be present, but it has not been shown to be predominant over the torsional effects, probably due to the extra damping afforded by the additional number of blade root fixings.

*General remarks on Vibration.* The use of electrical straingauging has served to determine the resultant vibratory stresses in the propeller both on the engine test hangar and in flight. Since the degree of stresses have been shown to vary between ground running and flight it has become essential to carry out flight strain-gauging on all propellers.

The compressed wood blade with its inherent capability of withstanding the effects of torsional vibrations does not suffer in this respect as much as does the duralumin or the hollow steel.

It is of the greatest importance that piston engine designers give very careful consideration to this problem by the provision of the appropriate crankshaft dampers in the early stages of the design, as development so far carried out has served to show the appropriate orders of vibration in both in-line and radial engines which give the greatest trouble to the propeller designer.

Many times the propeller designer has designed his propeller blade to satisfy aerodynamic and steady stress requirements, only to find on subsequent strain-gauging that a stiffening-up of the blade sections is necessary to reduce the vibratory stresses, thereby reducing the aerodynamic efficiency. If this issue does not receive the careful consideration requested it will play a big part in subscribing to the death knell of the piston engine, as all the efforts of the engine designer in increasing the powers will be negatived by inefficiently converting this power into useful thrust.

A preliminary examination has been made of a fluid drive between the engine and the propeller, the drive being sandwiched between the crankshaft and the reduction gear and running at crankshaft r.p.m. so as to reduce the diameter of the unit. The additive weight for a 2,000 h.p. engine was estimated at around 200 lb. While such a step may at first appear undesirable on the grounds of added weight and complication, something of this nature may have to be done if aerodynamically efficient propellers are to be used on piston engines of the future.

On the turbine propeller application the propeller designer is eagerly looking forward to the "vibrationless" characteristics of this unit, which if upheld in subsequent development will permit the use of metal blades with a thinness of aerofoil hitherto unknown, at the same time making possible a reduction in the hub weight by the use of thinner sections throughout.

## PROPELLER SYNCHRONIZATION

With the gradual return to multi-engined commercial air transports, synchronization of the propellers during flight has become an essential requirement for passenger comfort. The "beat" which occurs when the engines are running slightly out-of-step has always been a source of annoyance to passengers.

It is, however, just as important to make the synchronization automatic as it relieves the crew of the task of continually adjusting the engines by hand during flight and even then only obtaining reasonably good but still imperfect synchronization.

The automacity is still further essential since an annoying "beat" occurs when the engines are even the slightest amount out-of-step, a difference of only 20 r.p.m. between two engines will cause a distinct beat every three seconds. Such a condition could never be manually corrected on a tachometer, and would have to be done by "beat" elimination, and even so changes in conditions of flight can throw the engines out of phase again. Hence, automatic synchronization becomes an essential requirement. It is beyond the scope of this paper to go into the detail aspects of synchronization, but experience in America and this country to date has shown the practicability of several systems which confidently guarantees that future propellers in this class of aircraft will be automatically synchronized.

## PROPELLERS FOR ENGINES BETWEEN 100 and 1,000 B.H.P.

The main portion of the paper has dealt with aircraft applications where the designer has to strive very hard to justify the propeller as an efficient means of aircraft propulsion.

Of equal importance is the propeller application to smaller ranges of piston engine powers in aircraft installations such as single engine trainers, twin-engined trainers, private owners' single engined aircraft and feeder airlines.

For the *ab initio* single engine trainer application the latest engines are now being equipped with facilities to take the constant-speed propeller, and future training will, no doubt, include this feature at a much earlier stage than previously. The twin-engine trainer should be fitted with a fully feathering constant-speed propeller, as experience throughout the war has established the feathering feature as an essential on all twin-engined aircraft.

The private owner aircraft of the small single engine type will most likely only be interested in a fully automatic two-position propeller actuated by a balance of centrifugal force and thrust, providing him with the fine pitch to give the requisite take-off r.p.m. and changing into coarse pitch as the thrust reduces.

For the twin-engined feeder air-liner or freighter, the same propeller specification holds as for the military trainer edition, with the possibility of braking propellers for reducing landing run on relatively heavily loaded types.

On the twin-engined aircraft for "taxi" use the propeller will most probably be of the direct manually operated type with the possible assistance of a mechanical servo or electric motor actuation as an alternative to manual. In either case the requirement for feathering on all twin-engined aircraft will still hold.

The popularity of any of these types of propellers for the private-owner aircraft will be largely dependent on their having a low selling price and being capable of easy fitment and as simple as possible in construction to guarantee trouble-free service.

## PROPELLER SPECIFICATION FOR THE FUTURE.

N.B.—It should be clearly understood that this specification is not intended to cover propellers required before 1946, but rather is intended to provide a target design specification.

(1) There should be no major engine changes required to fit a given propeller type. Propeller designs should be as independent of the engine as possible.

(2) A maximum rate of pitch change of 45° per second is desired for braking and feathering propellers.

(3) Adequate pitch range to permit feathering and braking should be provided, *i.e.*, at least 125°. Consideration should

be given to constant speeding in negative pitch.

(4) Provision should be made for fitting hollow blades in the larger sizes, in order to keep down specific propeller weight.

(5) In case of damage to the pitch change system, the blades should either lock at the pitch in which they then are, or go automatically to approximately cruising pitch.

(6) Propeller hub sockets should be so designed as to reduce their height to an absolute minimum in order to reduce spinner diameter for turbine installations.

(7) The propeller pitch change mechanism should not be subject to freezing troubles.

(8) Adequate de-icing means must be incorporated for blades, spinners and fans.

(9) Convenient means of attaching spinners to the hub must be provided, with quick release and automatic locking.

(10) Pitch indicators and pitch locks should be available for development in the experimental stages.

(11) The governing system should be adaptable to two-speed engine reduction gears if they are used.

(12) External means for static and possibly dynamic balancing should be provided in the hub. Means for individual indexing of blades to permit aerodynamic balancing must be incorporated.

(13) The necessity of fitting geared engine cooling fans must be envisaged in designing propellers to the above specification. These fans may be either an engine or propeller component as convenient.

(14) The basic propeller type introduced by any firm to meet the above specification should be such that it can be used for a whole range of propeller sizes, single and contra-rotation and various numbers of blades. Interchangeability of parts should be an important design consideration.

## DISCUSSION

Mr. F. M. Owner (Bristol Aeroplane Company (Engines): Fellow): First he congratulated Mr. Fairhurst on the clear demonstration he had given that propellers had a future scope and that the announcement of their demise had been somewhat exaggerated.

After commenting on the dexterity with which Mr. Fairhurst had stated the controversial issue of the change-over from the piston engine to the gas turbine, and had avoided committing himself on the date of the change-over, Mr. Owner, in view of the title of the paper, discussed the problem of propellers for gas turbines.

As to the field for the propeller, he agreed that Fig. 11 was a very fair presentation of the facts, with the possible reservation that the simplicity of the jet unit might lead to its adoption at speeds of the order of 500 m.p.h. and over, bearing in mind also its decreased weight. The conclusion seemed certain that future fighters would not have propellers, except for specialized types such as deck landing aircraft. In passing, he said the propeller diameter limitation, given as 16 ft. for a fighter, did not appear to tally with Fig. 4, where the diameter of a propeller absorbing 4,000 h.p. at 40,000 ft. was $18\frac{1}{2}$ ft., not 16 ft. He asked if the difference between 500 and 550 m.p.h. would make $2\frac{1}{2}$ ft. difference in the diameter.

Since the advent of the atomic bomb had rendered the future of the heavy bomber purely speculative, we were left with the large military or civil transport as the chief field for the propeller turbine. He asked Mr. Fairhurst whether the reduction of efficiency consequent on reduction of propeller diameter, whether obtained by counter rotation or not, was justified for that class of aircraft. The point was of considerable importance to the turbine designer because, with large diameter propellers, reduction gears of high ratio would

be needed if propeller tip speeds and noise were to be kept down to a reasonable level.

Although Mr. Fairhurst had agreed that the problem of noise was becoming very important, he had no new solution to offer. Mr. Owner pointed out that the use of the separate propeller turbine incorporated in certain types of unit, and mentioned early in the paper, offered the dual advantage of reducing the cruising r.p.m. without the additional complication of the two-speed gear, whilst still permitting high propeller r.p.m. for take-off. Very rightly, considerable space had been devoted in the paper to the consideration of the aerodynamic importance of the blade root. That was vital where the air entry lay behind the propeller, and it was fortunate that the complete absence of vibration to be expected with turbines should make thinner blades practicable. In point of fact, the biter was likely to be bitten; whereas in the past the propeller designer had objected strenuously to the vibration level of the engine, the turbine designer might quite possibly have to object to the vibration level of the propeller! With single propellers it might only be necessary to keep well clear of the wing, fuselage or other propeller tips; but in the case of counter-rotating propellers there was an inherent aerodynamic excitation. He asked whether we might hope to make those vibrations reactionless so far as the turbine was concerned. In other words, since the main propeller torques cancelled one another, could we expect that the vibratory torques would also cancel?

Vibration was not, however, the only factor affecting blade root thickness, and with the thinner roots possible with turbines the flutter problem might raise its ugly head. Having seen mathematical papers on flutter, he was glad that it was Mr. Fairhurst's problem, and not his own; but he asked what Mr. Fairhurst proposed to do about it.

With regard to coupled engines (whether piston or turbine), it would appear that the adoption of the type defined in the paper as co-axial would aggravate the synchronization problem, if the stroboscopic effect were to be avoided. The alternative arrangement, whereby both halves of the propeller were driven by both engines with clutches, in the event of failure, eliminated both that problem and the feathering difficulty, with its associated braking problem. He asked which of those arrangements Mr. Fairhurst preferred.

Whilst on the subject of contra-rotating propellers, he said he was interested to know that quite wide spacing between the halves was desirable, because that view, which he shared with Mr. Fairhurst, was queried in the earlier stages of shaft standardization.

Finally, he endorsed Mr. Fairhurst's propeller specification for the future, but with considerably more emphasis on the advent of the pusher propeller. Whilst he fully appreciated the difficult problems to be solved in the development of gas turbine driven pusher propellers and their associated exhaust discharge problems, he urged that concentrated research and development work on that type of installation was much overdue.

Mr. C. H. Griffiths (M.A.P., Fellow) said the large-diameter propellers forecast for very high power turbine engines operating at 40,000 ft. would clearly not only be very heavy, judged by present standards, but could be expected to present difficulties to the aircraft designer, due to their large dimensions.

Whilst probably it was doubtful whether high altitude turbines of as much as 10,000 h.p. output would ever be fitted to aircraft as single units—the probable trend being towards more turbines of lower power—it would seem that the overall aircraft effects would be likely to lead to the use of smaller diameter propellers than those evaluated as optimum by Mr. Fairhurst. With such smaller diameters, the difference between the efficiencies of the propeller and the pure jet would be reduced, and if the extreme case mentioned should arise, there would probably be a tendency towards the use of the pure jet in order to avoid the propeller complications.

The curves in Figs. 6—9, however, showed how the propeller diameter could be reduced

by increasing the number of blades up to the limit of ten in a counter-rotating assembly. It might be that, if ever the extreme case in curves 7 and 9 had to be met, consideration should be given to the use of triple instead of dual rotation propellers. He asked for Mr. Fairhurst's comments on that suggestion, appreciating, of course, that triple rotation would leave in the torque reactions effects of one propeller absorbing one-third of the total power, and that the addition of the extra propeller would not be expected to help weight reduction.

With regard to strain gauging to determine propeller vibratory stresses, whilst he appreciated that tests made on the propeller on the ground might, and generally did, give different results from those made in flight, he queried the suggestion that flight strain gauging was necessary for all propellers. His understanding was that flight strain gauging, whilst desirable, became essential only in those cases where prohibitively high stresses for reasonable life operation were revealed in ground testing, whereas there had been instances in the opposite sense.

Commenting on the target specification for the future, included at the end of the paper, Mr. Griffiths agreed that everything possible should be done to avoid engine changes when it was required to fit a given propeller type; but he went further and suggested that the ideal target should be an entirely self-contained propeller requiring no engine change at all.

Mr. A. V. CLEAVER (Chief Project Engineer, de Havilland Propeller Division, Associate) said the broad general impression of the future scope of propellers which was left by Mr. Fairhurst's paper was one with which he could find little disagreement; but some detail points seemed to call for comment, and on some aspects a rather fuller discussion seemed desirable.

The author had asked for the comments and guidance of aircraft and engine constructors. In a number of cases their reactions might probably be expected to consist in saying that many of the cases for which Mr. Fairhurst had considered hypothetical propellers might not be required in practice. However, that did not imply a belief that, if necessary, such propellers could not be provided. As an instance of his meaning, Mr. Cleaver said it seemed very unlikely that a piston-engined fighter giving conditions of 4,000 b.h.p./40,000 ft. at 550 m.p.h. would be worth building. It might be thought debatable also as to whether the future trend of aircraft size, performance and type of propulsion would call for the building of 10,000 b.h.p. at 40,000 ft. engine-driven propellers.

The distinction which Mr. Fairhurst had drawn between propeller-driving gas turbines and straight jet engines with propeller thrust augmentors seemed raher artificial, although it was quite clear what he had in mind. For so-called thrust augmentation on turbine engines using a hot jet as the main propulsive agent, one would have thought the ducted fan (possibly after burning in the duct as and when required) might have found one of its most useful applications. Perhaps one might almost say one of its very few useful applications, because there seemed to be only very few cases where a ducted fan engine was likely to compete successfully with either of the other two alternatives—the propeller turbine and the pure jet.

In discussing the possibilities of two-speed propeller reduction gears one would have expected Mr. Fairhurst to have made more of the particular advantages of that device on gas turbines. That type of engine had an extremely high available take-off horse power in relation to the power available for the top speed at altitude design condition. More important still, at any rate for transport aircraft, the rated cruising r.p.m. of a gas turbine were likely to be some 95% of the maximum rated take-off r.p.m.

All those factors taken together meant that a turbine-driven propeller designed for reasonable top speed and cruising propulsive efficiency, and noise leevl—a most important matter—would have a combination of dia-

meter, solidity and reduction gear ratio which was unfavourable for good performance at take-off and climb. All those objections could be overcome by the use of a two-speed reduction gear; in fact, such a device had a much greater value on a turbine-engined aircraft than on a piston-engined one of similar design conditions of power and air speed at altitude.

In view of the preference of the gas turbine for being cruised at high power outputs, which implied high air speeds, one was tempted to suggest that the turbine-propeller powered aeroplane should have a relatively high wing loading, so that it cruised at those high air speeds at a favourable altitude, and should also have the advantage of a two-speed gear. By means of that, extremely high propeller take-off thrusts could be obtained, giving reasonable take-off runs even with the high wing loading. An alternative to the two-speed gear, of course, on a turbine, would be any development permitting greater flexibility of r.p.m. operation of the engines, *i.e.*, the propeller might be driven by a separate component of a compounded turbine engine, which could be cruised at a much lower percentage of maximum r.p.m. than the 95% mentioned.

Although Mr. Fairhurst had made some reference to variable pitch propeller control problems on gas turbines, one regretted that he had not made more. The governing problems of constant speed propellers on gas turbines would be many and varied, although it was not desired to suggest that they would be by any means insuperable. Attention should be directed towards the large differences in the nature of those problems which would arise on different layouts of propeller-driving turbines. For example, those in which the propeller was driven by a separate free-running turbine would call for extreme measures to prevent possible overspeeding. On the other hand, those in which the compressor system, or any large part of it, was mechanically connected to the propeller shaft system would have the opposite characteristic. That was alluded to in the section of the paper dealing with braking propellers, where the references to the "rather higher" motoring power of such engines as compared with piston engines was a decided under-statement. Those turbines with large compressors on the propeller shaft system would introduce their own propeller governing problems, associated with the considerable lag introduced into the governing system by the large energy storage characteristic of the compressor. That would tend to cause hunting.

He felt that the author had dismissed the difficulties of reactionless modes of vibration rather lightly. Experience indicated that, with large propellers of diameter greater than 15 ft., especially with wide blades, aerodynamically-excited reactionless modes of vibration could be very troublesome. They would provide the propeller designer with very serious problems when he attempted to build large 8- or 10-bladed counter-rotating propellers.

On the subject of counter-rotation one would like to see some amplification of the author's reference to unequal speeds and diameters causing vibration and *hence* efficiency loss. The "hence" part of the statement in particular seemed rather obscure. Also, surely there was not much case for research on the spacing between contraprop halves, since the evidence which did exist showed that that was not very critical.

He agreed entirely with the author's staement that efficient propeller de-icing must rank as an important safety feature on future aircraft. Even so, one felt that in certain quarters the dangers of propeller icing had been rather exaggerated. A desire to provide propeller de-icing should not be carried to the extent where it sanctioned the fitment of devices which might result in a permanent built-in propeller efficiency loss almost as serious as the occasional loss in performance which might be encountered due to ice accretion.

That objection might possibly be applied to some of the rubber overshoe schemes, for

which there was enthusiasm in certain quarters. Admittedly no data existed to prove the point definitely; but that merely pointed to the desirability of obtaining it, and also similar definite information of what efficiency loss might be caused by the order of propeller ice accretion which could reasonably be expected in practice.

The advent of the hollow steel blade would introduce the possibility of improved propeller de-icing schemes not subject to that criticism. On other grounds, as indicated by Mr. Fairhurst, the introduction of hollow steel bladed propellers for future large sizes seemed so highly desirable as to be, in effect, inevitable.

Dr. H. C. WATTS (Airscrew Co.: Fellow) recalled that almost exactly nine years previously he had tried to forecast the airscrew developments of the following ten years. He had said then that for speeds up to 140, 250, and 350 m.p.h., the fixed pitch, two pitch and constant speed propeller respectively would hold the field, but for speeds above 350 m.p.h. there would be required a constant speed propeller combined with a two-speed gear. He had added that he had not thought it necessary to go further, but, should mankind every fly at more than 500 m.p.h.—which at that time seemed to be an awful speed—a demand would probably arise for three gears, unless the type of airscrew used in 1936 had been replaced by some form of jet propulsion. He thought his forecast had proved substantially correct.

In the paper Mr. Fairhurst had tried to answer the question as to whether propellers were done with completely. Dr. Watts' answer to the question was "No." He believed the forecast he had made nine years previously would remain substantially correct, and that for speeds above 450 m.p.h. the propeller-less machine would hold the field.

Mr. Fairhurst quoted 550 m.p.h., but bearing in mind the desperate struggle necessary to make a propeller function at so high a speed and on the other hand that jet propulsion was still in its infancy and afforded great simplification in power plants generally he thought his figure of 450 for the change-over likely to be nearer the mark.

Nevertheless, at these high speeds both propeller and jet used separately were in difficulties, the propeller because of the excessive tip speed and poor take-off without two or even three speed gears and the jet because of very poor take-off.

For machines of the fighter class or similar civil duty, low efficiency at take-off might not matter and for such machines jet propulsion would, in his opinion, hold the field alone. For a machine which required a good take-off combined with high tip speed, he was attracted to the lecturer's suggestion of a thrust augmenting combination of propellers designed for low speed and jet for high speed.

Discussing the types of materials for propellers, Dr. Watts said he was in general agreement with the author in backing the possibility of the use of the hollow steel blade in the future. It was pioneered in this country, but it came to a sticky end in the 1930s, due more to lack of financial support than to anything else; but he still believed it had a distinct future. For large propellers it offered the best chance of reducing weight; whilst he shared the author's doubt as to whether it would give the necessary clean section for high speed propellers, on the other hand he doubted also that for high speeds we should be able to use propellers at all, believing that in that field jet propulsion would be used. For some time to come, however, duralumin would still hold the field. Again, he did not think the use of wood had ended altogether, for it had advantages in respect of weight and also of low gyroscopic stresses to react on the life of the engine. But the disadvantage that it was hygroscopic was not fully realized; it was true that the wood absorbed moisture very slowly, but in course of time that absorption would tend to alter the balance. During war-time that disadvantage was not felt greatly, because the life of a propeller was so short, but it might be more important in peace-time. He would not say

that we could not produce compressed wood which was completely non-hygroscopic; but in so far as we did that we should create difficulties in respect of glueing the material together and we should lose the great advantage of the wooden propeller that it was easily repaired. The continued life of the wood propeller depended on the development of better coverings to prevent absorption of moisture. Its use should not be dropped. Certainly it had saved the position at the beginning of the war because, fortunately, before the war we were in a position to produce it. Wars were not yet over, and a position might arise again such as he had experienced during the war, when the wooden propeller people at the Air Ministry had said that the conditions must be met by metal propellers, and the metal propeller people had said that it must be met by wooden propellers. Therefore, it was desirable to keep all possible types of propellers in production.

Discussing the almost desperate measures to which the designer had to resort in order to get down to thinner and thinner sections and achieve higher and higher efficiencies, he said that so far most people had worked, not only on thinning the sections, but also on changing the centre line camber, thereby arriving at a low lift section. It had always been his opinion that the best section—apart from the difficulties of production—was a very thin streamlined section developed on a circular arc of, say, T/C equal to about 0.075. It was true that it would give a reflex trailing edge and that it would be horrible to manufacture; but if we wanted efficiency we should have to give that section consideration.

Mr. F. C. LYNAM (Airscrew Co.: Fellow) said the paper contained a lot of information, but he regarded it as rather superficial; the details which had enabled the author to arrive at his conclusions Nos. 1—13 were not available. Reference was made by the author to the absence of technical jargon; but Mr. Lynam suggested from experience that such information must be made available, at least at a meeting of the Royal Aeronautical Society, if conclusions on propeller development were to be followed.

It seemed to him that conclusions Nos. 1—5 could be replaced by saying that the future scope of propellers was dependent on the correct combination of propeller diameter and solidity with rotational speed to suit the aircraft speed required and the h.p. available. That was really a summing-up of the pictorial analysis on Figs. 20 and 21.

The use of a two-speed gear, which was under consideration ten years ago, appeared to be absolutely necessary in conjunction with constant speed propellers if a satisfactory ratio of thrust to h.p. at take-off were to be obtained. In Mr. Lynam's opinion, that figure should not be less than 5 lb. per h.p. where the design condition at altitude was 500 m.p.h. or over. That equally applied, although perhaps it was not practicable, in the case of the straight jet with a propeller as thrust augmenter, where it was estimated that the take-off and initial climb would be improved by 45—50%. Without having had the opportunity to make detailed calculations, he imagined that in that instance a thrust/h.p. ratio of at least 4.5 was required.

Commenting on the author's references to the thickness/chord ratio of the root sections of propeller blades, and his view that reduction must be made to within 16%, Mr. Lynam agreed that obviously any reduction was worth while, but he suggested that the inboard portion of the blade was of little use in high speed flight; compressibility losses were building up, and with the low rotational speed of the inboard sections, reverse thrust was bound to occur. What was required, at least theoretically, was that the spinner size should be increased to the point where, with present blade designs, the camber ratio is approximately 16%.

Comparison of blade materials was always a vexed question, and he could not agree with some of the remarks in the paper concerning the comparison of wood with duralumin. He would have thought it quite impracticable to fit a wooden blade in the same hub as was

used for its dural counterpart, if full advantage had been taken of the material when designing the hub for the dural blade. His experience had been connected with the necessary addition of a metal hub adaptor on a wooden blade, which increased the weight as much as 20% and increased the size of the wooden root as much as $\frac{1}{2}$ in. There might be other means of anchoring the wooden blade, but it is anticipated that the weight would be increased and, where small hubs and spinners are used, inferior aerodynamic features would result.

Commenting again on the pictorial analysis of future propeller types in Figs. 20 and 21, he said the comparisons between wood and duralumin were interesting; but without wishing to embark on a discussion on weights, he suggested that the claims for wood were exceedingly optimistic. The estimated weights for hollow steel should have been included, for obviously the author considered that hollow steel construction was likely to be used to a far greater extent in the future.

The question of blade materials was also connected with the availability of power for turning the blades and overcoming the blade twisting moments. Frequently it was not possible to take full advantage of particular materials for design, owing to the limitations imposed by the power available.

In conclusion, he reminded the author that, where he had spoken of the compressed wood blade, initially developed in Germany and taken up in this country before the war, the compressed wood portion was associated entirely with the blade root and natural wood was used for the main blade material. Those were the blades which were available in quantity in the early days of the war.

Group Captain P. W. S. Bulman (Hawker Aircraft: Fellow) said that he was glad to see that the author had included a section on the braking propeller. It was interesting to recall that the earliest development of the variable pitch propeller was to meet the airship requirement for providing a power-on condition of braking when approaching a mooring mast. There was a similar requirement to provide an air brake and to shorten he landing run of aircraft to-day, and this may well become of greater importance with the propeller turbine of to-morrow, with its slower response to power control. Power-on braking at high speeds may prove too onerous a requirement and windmilling may well have to be accepted as a compromise. The suggestion, however, that windmilling could not be employed at the highest voluntary or involuntary speeds, or, as the author stated, applied at above 300 m.p.h., would prove a great operational handicap as well as presenting a complex control problem. It seemed to him rather like the 100 m.p.h. car on which the brakes could not be used over 60 m.p.h.

In considering the gas turbine with propeller, the choice of gear ratio would need consideration, owing to the probability that this type of power unit would cruise at a higher percentage of its maximum r.p.m. When making the comparison with existing practice, it should not be forgotten that piston engines, particularly in transport aircraft, are rarely called on to cruise at more than 50% power and relatively low r.p.m., with corresponding improvement in propeller efficiency and reduction in noise level. In this connection, he pointed out, current combinations of propeller shaft, crankshaft and blower ratios were frequently not optimum for the purpose for which the aircraft was normally used, and in certain instances, an all-round improvement would result from reducing the crankshaft r.p.m. for given propeller and blower speeds.

Mr. C. F. Hodson (Fairey Aviation Company: Associate Fellow) recalled that his Company, the first in the world to do so, had 3+3 blader contra-rotating propellers flying in 1939. He complained that Figure 3 omitted this fact and that although it left room for it to be recorded in the left-hand top corner, there was insufficient space to indicate what results could have been ex-

pected if that type of propeller had then been adopted.

Commenting on the author's reference to aerodynamic balancing for thrust and torque, he asked whether the author had really meant torque rather than torque forces.

About fifteen years ago the Fairey Aviation Company had adopted the dynamic balancing of all propellers as their normal routine, and had continued with the practice for a number of years. Eventually, it was found that improved methods of manufacture rendered this operation unnecessary, and it was largely discontinued. He suggested that possibly Mr. Fairhurst might have the same experience.

Mr. W. U. SNELL (De Havilland Propeller Division: Associate Fellow) was gratified that Mr. Fairhurst had not attempted in the paper to make out a particularly strong case for the compressed wood propeller blade. Indeed, the general trend of his comments on blade materials was such that one could not quarrel with it very seriously, although a few points of detail were worth taking up.

For instance, it was considered rather optimistic to suggest that the wooden blade would show literally no performance loss as compared with the thinner metal one at top speeds as high as 450 m.p.h. Also, a claim for the repair advantages of the wooden blade should surely be qualified by pointing out that wooden blade repair frequently involves an expenditure of man hours equivalent to building a new blade on to the existing root and adaptor.

In this country more than 80,000 duralumin blades had been repaired, and experience to date had proved that the scrap rate was exactly one-third. Of the two-thirds which were repairable, about one half required heat treatment before and after repair, and the other half could be straightened without recourse to heat treatment. Including the worst repairs which had been undertaken, the average time cycle of repair was 20 hours, including furnace and processing times.

It might be argued that the age-hardening period of 72 hours prohibited quick repair; but in practice, repaired blades were always being assembled in their hubs during that period. On the other hand, during wooden blade repair there were frequent gaps of long periods, such as 12—24 hours, to allow glued joints to harden, and during those periods nothing was being done to the blades.

There was ample proof that duralumin blades never shattered under the impact of crash landings or enemy action by machine guns, cannon fire or anti-aircraft fire. In fact, at one stage during the war, bullet hole repairs were within the capabilities of normal squadron personnel, who simply cleaned the hole out, inspected for cracks and sent the aircraft off on service again.

As an example of what could happen when using metal bladed propellers, Mr. Snell said that one had come back from Germany with a hole near the tip. The pilot did not know, and he believed the ground staff also had not noticed it! Imagine what would have happened to a wooden blade in those circumstances!

With regard to propeller weight, he said the author had suggested that some day the dural blade might be developed so that it would have the further advantage of permitting smaller hub sizes than wood, because future dural blade roots might be appreciably smaller in diameter than wood. Mr. Snell pointed out, however, that this was no mere hypothetical future development, but was already an established practice, provided a form of retention for the dural blade was used which did not involve a threaded sleeve or other feature introducing stress concentrations. With such a favourable retention, dural propellers could already have smaller roots, hence smaller hub sizes, than wood. With a more unfavourable retention the dural blade could be, and sometimes was, unfairly handicapped in comparison with wood.

That point might explain the generally optimistic weight advantage shown throughout the paper for wooden as compared with dural propellers. On an important new

British transport aircraft the difference in weight between alternative wooden and metal propellers was only 7 lb.

It was also suggested by the author that in the case of four-bladers of about 14—16 ft. diameter, a wooden propeller would be some 25% lighter than dural. An advantage of 10%, however, would be nearer the truth if full advantage were taken of the potentialities of dural as previously indicated. Similarly, the even larger weight advantages for wood shown for still bigger propellers were believed to be even more optimistic.

Then it was suggested that hollow steel bladed propellers would come out heavier than compressed wood throughout the entire range. There again, provided the best possible design of hollow steel blade were considered, *i.e.*, one built up from a light shell attached to a spar as main structural member—that statement was unfair to the metal blade. On a 14—16 ft. diameter four-blader, where the solid dural blade might have a 10% weight disadvantage as compared with compressed wood, such a hollow steel propeller could show a weight reduction of about 5% compared with wood.

Commenting that he did not understand the author's statement that "by far the major portion of the weight of a propeller comprises blades," Mr. Snell pointed out that normally blade weight accounted for 50—60% of total propeller weight, regardless of the type of blade material involved.

The pictorial analysis of future propeller types in Figs. 20 and 21 showed surprising, and in some cases apparently illogical, variations of propeller weight and diameter with power. For example, the weight of a "double three" 18 ft. propeller for 5,000 h.p. was indicated as 1,450 lb. as compared with only 1,300 lb. for an exactly similar 6,000 b.h.p. propeller. Criticisms of a generally similar nature could be levelled against some parts of Figures 6—9, showing propeller diameters for turbine types. On the first of those, for example, a 14 ft. four-blader was suggested as suitable for 2,000 b.h.p. In comparison with that, a double four-blader might be expected to absorb efficiently something like twice that power, but by the exercise of some special un-Fairhurst ingenuity it appeared that such a propeller could really cope with 6,000 b.h.p., *i.e.*, three times the power.

The author seemed to think that there was some special advantage in small diameter multi-bladed propellers on gas turbines, since they permitted smaller undercarriage heights, etc. It was difficult to see the basis for that. Surely for a given power, altitude and airspeed a certain propeller diameter was desirable, regardless of whether the engine was turbine or reciprocating. Any trend towards using unduly small diameters on turbines, as compared with piston engines, would penalize propeller performance on such installations to a most undesirable extent.

Why did the author consider the use of power-on airbrake propellers might introduce aircraft control difficulties, as compared with similar windmilling brakes? Was he thinking of slipstream rotation effects, which could be minimized by the use of counter-rotation? It was agreed, however, that the windmilling airbrake propeller might be an easier proposition from some aspects not associated with aircraft control.

Finally, it was very interesting to see that Mr. Fairhurst had placed on record a specification for future propellers, which one recollected having seen in substantially similar form from various American and British sources over the past few years. About a year ago, in discussions with Mr. Fairhurst, Mr. Snell had found that, while agreeing with such a specification in general principle, Mr. Fairhurst had objected in detail to the inclusion of various of the features he had now adopted, and it was gratifying to note that Mr. Fairhurst had taken this opportunity of placing on record his agreement. It was also extremely interesting to note that, by implication, Mr. Fairhurst was now apparently prepared to provide propellers to that specification within the next few months, since he had retained the 1946 target date

which was suggested at the time of the original discussions already mentioned.

Captain J. MORRIS (R.A.E.) said that in the old days a propeller was fitted to a ship or an aircraft in much the same way as the ironmonger added the word "Esquire" after a customer's name. But they had progressed far since then. A case which he believed had had a big influence on propeller design arose some years ago. A shipbuilder had ordered a propeller from a well-known firm and, when it was tried out, the vibration was so bad that the ship could not pass its trials. In consequence an action was taken by the shipbuilder against the propeller makers on the grounds that the propeller ought to be such as to make the ship seaworthy; eventually the case reached the House of Lords, where it was held that it was the responsibility of the propeller people to supply a proper propeller.

The same sort of development had happened in respect of aircraft. Failures began to arise such as charred bosses on the old wooden propellers, and so on. The first attempt was to treat the vibration as arising from a combination of crankshaft and propeller, in which the propeller was regarded as a rigid pulley in the plane of rotation; but they had since travelled a very long way and had coupled up the propeller vibration with the whole aircraft. So it seemed that the propeller was playing a much more important role than was at one time imagined, and a good many headaches had been experienced in coping with it. Probably they had made more progress in this country, however, than had the rest of the world put together, which was a matter for great credit to the propeller specialists; he believed the aircraft propeller people had adopted the attitude that, inasmuch as nobody else seemed to accept responsibility for the vibration of the whole aircraft, they must do it, and they were doing it very well.

Finally, Captain Morris acknowledged the very great help and encouragement he had received in his personal investigations, not only from the Council of the Royal Aeronautical Society, but also from Messrs. Rotol Ltd., and other firms.

Mr. O. N. LAWRENCE (Joseph Lucas Ltd.: Associate Fellow) *contributed*: Mr. Fairhurst mentioned the control of the jet and propeller thrust augmenter layout. He could confirm that with the "straight" jet engine, the aircraft speeds made little difference to the r.p.m. of the engine, although the available power increased. This increase applied to the full throttle condition; at smaller throttle openings, of course, the effect of windmilling became noticeable. Hence, as Mr. Fairhurst suggested, a small propeller augmenter would probably not behave efficiently under the control of a conventional C.S. governor unit.

A modified control principle was ready to hand; the power obtainable from one of these engines could be approximately expressed for any given r.p.m. as a unique function of Nacelle Pressure, *i.e.*, Ambient Atmospheric Pressure plus ram pressure, and this was made use of in the fuel control system. By a suitable design of Reduction Gear, either the torque or the power transmitted through the gearing to the airscrew could be converted into a hydraulic pressure. This pressure could then be used on a unit identical with, or very similar to, the fuel control unit, to operate a servo system governing the pitch of the propeller.

Mr. Fairhurst had pointed out that under "All-out Level" conditions, it would probably be necessary to feather the propeller. He imagined that he also assumed that it could be prevented from rotating as otherwise the paddle wheel action would seem to result in considerable losses. This, anyway, would imply a modified system of reduction gearing and this, incidentally, could easily be designed around the gadget required for giving the power measurement.

Regarding the general question of fitting a propeller to a gas turbine engine, it would seem very likely that the engine would accelerate too rapidly for the C.S. governor to alter the pitch quickly enough to prevent overspeeding occurring. This implied that an

overspeed governor must be fitted to such a combination, working on the fuel supply to the engine, in a comparable fashion to the ones fitted on jet engines. The propeller governor would need to be set somewhat below the setting of the overspeed governor to prevent one fighting the other.

Mr. F. Nixon (Rolls Royce Ltd.: Fellow) *contributed*: The author was to be congratulated upon the breadth of the survey which he had made of the problem. While he had left no doubt that the propeller was assured of its place in the future, and had administered a healthy corrective to those who had seen in jet propulsion the end of all rotational propulsion, he had, in the mind of Mr. Nixon at least, left a slight tinge of regret. It would appear that in his enthusiasm for bigger and bigger propellers, the author had left himself no time to descant on better ones.

It was inevitable, so soon after the end of the war, that military considerations should preponderate. However, in reviewing the probable developments of the next five years it was of the greatest importance to give proper place to civil air transport. While development in military aircraft would continue, the keenest competition would exist in the field of passenger and freight carriers. Within the period under review, it was most unlikely that they would see cruising speeds much in excess of 300 m.p.h., nor operating altitudes above 25,000 ft., except in prototypes. Under these conditions, however, there would be considerable scope for propellers of greater efficiency, greater reliability,lighter weight, longer life, and lower first cost. During the war it would have been exceptional if the propeller designer had not had to shelve with regret, for reasons of military or strategic expediency, developments which would to-day be of prime value to the airline operator, and it would be interesting to hear of these.

The reiterated request of the author for fuller co-operation from the engine and aircraft designer would have to be granted before maximum efficiency was achieved. With this in view, it was unfortunate that the broad scope of the paper had precluded more than a superficial reference to certain aspects of interest to those other branches. It would, for instance, be useful to an engine designer to be given some idea of the relationship between engine torque fluctuations and propeller weight. What, for example, was the weight penalty of 9 or 12 or 14 or 24 or 28 cylinders, as compared with a turbine? And to what extent could this be offset by a fluid drive, or other form of damping? The engine designer too would be glad to have more guidance on the means of operation of the propeller, whether hydraulic or electric, or both, as the accommodation of the necessary equipment and controls within the power plant was becoming increasingly difficult.

On his part, the aircraft designer would doubtless welcome more specific information on installation and nacelle position and blade tip clearance as affecting vibration due to aerodynamic excitation. In this connection it was somewhat surprising that pusher propellers were not mentioned.

Still pursuing the matter of collaboration in the search for maximum efficiency, it was felt that this could only be enlisted by the widest possible dissemination of information regarding the problems confronting the propeller designer. It was disappointing not to find in the paper some mention of propeller actuation. What were the author's views on the power supply, how would this be applied, and what limitations on blade weight and propeller diameter were imposed by the capacity of the blade bearings? Then it was possible that developments in blade bearings might have useful applications in other directions, while details of the power transmitted, the gear ratios, weight, and overall efficiency of hub mechanisms would be of the greatest interest to mechanical engineers and would serve, too, to give some measure of the progress made in propeller design.

Regarding the probable size of turbine engines, covered by Fig. 10, it was thought that the author had been excessively pessimistic, and that he would have been quite safe in flattening the curve off at a diameter certainly not in excess of 6 feet.

On the question of blade materials, the hollow steel blade was now reaching a high stage of development in the United States, but it was understood that the thin hollow section had in some cases given rise to unpleasant noise. It was known that the author's Company had been highly successful during the war in its efforts to repair both wooden and duralumin blades. When airlines were again established on a competitive basis it was probable that repairability would become just as important in order to keep down replacement costs as it had been during the war to maintain numbers, and in this respect the wooden blade might score over the hollow steel one.

It was natural, after 10 years' preoccupation with military requirements, that there should be a tendency to assume that what applied to large sizes would apply equally well to equipment for small private aircraft. This was by no means the case, and it was submitted that there was as much scope for research and development in this field as there was for higher powers. Such work would be fully justified, as it was extremely probable that within the period under review the small private machine would play an extremely large part, measured in volume of business.

Mr. J. V. Inglesby (M.A.P.: Associate Fellow) *contributed*: There was no mention of flutter in the paper. This was hard to understand in view of the fact that a number of compressed wood blades had been rejected on that score and in some cases fractures had occurred in flutter spin tests. It was flutter that limited the fineness of wooden blades.

It seemed that the real weakness of wooden blades lay in it being almost impossible to inspect beneath the leading edge sheath to see the effect of innumerable screws or rivets attaching the sheath on the somewhat slender leading edge. Could anything be done to improve this?

Mr. J. A. C. Williams (Associate Fellow) *contributed*: Mr. Fairhurst's paper was opportune in that a need for research on propellers was expressed at a time when the authorities concerned must be considering expenditure upon research. Many aerodynamic design problems, such as the relative performance of wide blades compared with narrow blades were unsolved, and it was for the good of the community that they be resolved. Fig. 11 illustrated that for speeds up to 550 m.p.h. the propeller gave the highest efficiency of the known forms of propulsion; civil air liners, indeed most aircraft, travelled far below this speed, and it was to be hoped that a little attention would be given to propulsion research for such aircraft. It was too often forgotten that top speed was seldom realized in the life of many machines, especially if they were civil air liners, and that climb performance was of greater importance.

The paper touched upon noise problems in so far as it admitted their ignorance and expressed a need for research into obtaining lower cabin noise levels. Surely as great a need existed in reducing noise at the source because of the nuisance to housedwellers near aerodromes? It was generally considered that the noise source of propellers was the high Mach No. compressibility wave but axial flow fans at 200 ft./sec. tip speed had no such source yet could give sound energy values of over 110 decibels. The sound energy for fans (and they presumed propellers) varied as approximately the seventh power of the tip speed and therefore if run at propeller tip speeds would be expected to give sound levels considerably in excess of that obtained on propellers. The reduction of noise level was of

importance in the development of axial flow fans for mining and house ventilation and for wind tunnels. In the latter case the noise generated could affect the transition point on the models. If the needed research upon noise was instituted it was to be hoped that the whole gamut of rotating aerofoil applications would be treated.

## MR. FAIRHURST'S REPLY TO THE DISCUSSION

*Mr. Owner.* Referring to the question concerning the reduction of the diameter of propellers by multi-blading and rotating faster, in order to ensure the least nuisance to the aircraft man in designing the undercarriage, several tests had been carried out so far, but unfortunately none of them were very conclusive. Tests were still being made on a certain installation, where attempts were made to reproduce the conditions of the much smaller diameter six-bladed propeller as against the normal four-bladed type. However, his Company had gone into the matter carefully in connection with the latest high-powered piston-engined fighters for deck landing; and he gave figures to show how the percentage varied.

For a particular installation, a 3,000 h.p. fighter, with an all-out level speed of 470 m.p.h. at 15,000 ft., a cruising speed of 300 m.p.h. at 2,100 h.p. at 15,000 ft., and a climb of 170 A.S.I. at 2,500 h.p. at 15,000 ft., if one had not to limit the diameter of the propeller, a four-blader, of 16 ft. diameter, running at 1,200 r.p.m., would give an efficiency at all-out level of 82%, a cruise efficiency of 85½%, a climb efficiency of 80%, and a take-off thrust at 60 m.p.h. of 8,500 lb.

If the number of blades was increased to six by using counter-rotation, reducing the diameter to 11 ft. and still running at 1,200 r.p.m., the all-out level efficiency would drop to 81%, the cruise efficiency would drop to 82%, the climb efficiency would drop from 80% to 76%, and the take-off thrust at 60 m.p.h. would drop to 4,000 lb.

Using a six-blader, again of 11 ft. diameter, and running at 1,500 instead of 1,200 r.p.m., the all-out level efficiency would remain at 82%, as in the case of the four-blader; the cruise efficiency fell by ½% to 85%; the climb efficiency dropped from 80% to 77%; and the take-off thrust was reduced from 8,500 lb. to 6,000 lb.

He had taken the matter a stage further and had examined the case of an eight-bladed propeller of 9½ ft. diameter, running at 1,500 r.p.m., the same speed as the six-bladed high-revving propeller. The all-out level efficiency then dropped by 2%; the cruise efficiency dropped by 3½%; the climb efficiency by 3%; and the take-off thrust would drop to 5,000 lb.

Thus it would appear that, for an installation which normally would be fitted with a four-bladed 16 ft. diameter propeller running at 1,200 r.p.m., except for the reduced efficiency in the climbing condition, one could reproduce the all-out level and cruise conditions with a six-blader of 5ft. less diameter, running at 1,500 r.p.m. instead of 1,200 r.p.m.

However, these figures had yet to be proved; they were merely the result of an examination of the data already available.

He did not think many people knew a lot about noise and its prevention; very little in this country seemed to have been written about it. The problem had suddenly come upon us due to the rush to produce civil aircraft; and he believed that it was accounted for largely by the fact that we had to make quick conversions of existing war-time aeroplanes.

In approaching the problem of aircraft noise, taking the aircraft as a whole, it was first essential to differentiate between the treatment of the noise levels at the higher and the lower frequencies. For convenience one might regard the frequencies above 300 cycles per second as the high frequencies. Noise level at the high frequencies could usually be reduced by efficient sound-proof-

ing; and that was the aircraft manufacturer's problem. It was important to ensure that all gaps in the fuselage were sealed; a window which was just a little open, for instance, would admit almost as much noise as a window fully open.

The problem of dealing with noise at low frequencies was rather on the plate of the engine and propeller designers. One could not deal with noise at frequencies below 300 c.p.s. by sound-proofing; at such frequencies the noise level of the engine and propeller was at the maximum, one could not treat it other than by getting down to the source of the trouble. In reducing the noise level it should be appreciated that a reduction of the total noise level entailed a considerable reduction of the level of each source; even if one source of noise were removed entirely, the total noise level would not be reduced by more than a few decibels. But if there were two noise sources and the level of both of them were halved, one could notice quite an appreciable difference.

So far as we could see at present, based mostly on American experience, it seemed that an accepted sound level at the low frequency end was round about 98—100 decibels. From the propeller standpoint the tip speed was the major component responsible for the propeller noise. Reduction of the tip speed would reduce noise level; but such a step would naturally be very limited and impracticable, because the aerodynamic efficiency of the propeller would suffer. Again, if the propeller tips pass very close to the fuselage, cropping of the propeller in order to increase the clearance would reduce the noise level; but one could not reduce diameter without impairing the aerodynamic efficiency.

So far, therefore, we could do little about aircraft converted from service types. But he had stated the problems in order to ensure that, in the design of an entirely new aircraft, consideration was given to propeller tip clearance when fixing the positions of the engines outwards from the fuselage and longitudinally relative to the cabins of the aircraft. For that reason the propeller designer must immediately carry out some intensive development, for he considered the propeller designer should advise the aircraft manufacturer of the requirements of clearances of the propellers.

Dealing with propeller vibration, Mr. Fairhurst discussed the forms of vibration which have to be dealt with, starting firstly with the steps taken to obtain the minimum out-of-balance of the propeller. The various forms of unbalance which could occur are static, dynamic, aerodynamic, and engine and installation excitation. With regard to static balancing, little or no trouble is experienced from this source, since the latest technique enabled propellers to be balanced to a very fine degree. Dynamic balancing had not been carried out during the war owing to its "slowing-up" of production; static balancing at 0° and 90°, and also in some cases at the top speed flight angle had sufficed to cover the dynamic condition.

Aerodynamic balancing he divided into thrust balancing and torque balancing. Balancing for either of these conditions was necessary because one could not make propeller blades without having manufacturing tolerances, and as such each blade had differing characteristics of thrust and torque. There was a system in vogue whereby propellers could be thrust balanced on a production basis and any trouble in that direction removed. But in certain installations it was not altogether the thrust balance that presented the problem; it was rather the torque balance, so that balancing had to be carried out to guarantee each blade having an equal share of the torque. A propeller could not be both thrust and torque balanced but by concentrating on the more serious of the two there was a reduction in the out-of-balance of the other.

But it was evident that, even after thrust balancing or torque balancing a propeller, something more had to be done. Very severe vibrations had been reported at high

forward speeds, even though the propellers had been thrust balanced or, according to the type of aeroplane, torque balanced. These vibrations had occurred due to the out-of-balance caused by slight eccentricities of the propeller on its shaft. His colleagues had devised a meter whereby they could carry out the final balancing of a propeller on the aeroplane with the engine *in situ*. In the heavier classes of aeroplane, the balance correction could be done on the ground; at the moment the fighter aeroplane was rather tiresome in that respect, for one had to make about three check flights before arriving at the final answer.

Assuming the propeller was balanced as efficiently as is now practicable, he did not think Mr. Owner need be greatly concerned about the vibrations excited by the various out-of-balance conditions, for he did not think they would be such as to affect the turbine unit.

*Mr. Owner said his major point concerned the fed-back interference vibration.*

Mr. Fairhurst replied that he had had no experience of that. The only case in which he feared there might be some chance of vibration being fed back was where the system was running on a resonant frequency.

On the question of blade flutter, the problems we were up against on the propeller side were the stalled flutter, which would usually occur at around take-off and initial climb, and the classical flutter, at low incidence, which might occur at cruising, all-out level or high speed climb. Where a propeller blade had been reported to suffer from flutter, if it were the classical variety, we had achieved successful results by cutting back the leading edge of the propeller at the outboard sections, providing the flutter was confined to the outboard sections. That had the effect of moving the centre of pressure of the blade on to the flexural axis of the blade.

So far they had not arrived at any definite method of eliminating stall flutter.

The aural method of recording flutter was very unsatisfactory, and in conjunction with R.A.E. they were developing the measurement of flutter by strain gauges on the propeller tips. The latter method told them, not only the degree of fluttering, but also the stresses, in lb. per sq. inch on the blades. At the moment they relied on a very experienced operator to aurally determine the degree of flutter that was occurring. With years of experience one could be a very good judge, but one might still be in the position of accepting a propeller having a certain amount of flutter, but which was not detectable aurally. By means of the strain-gauge method one could get down to actual numerical stress values and could perhaps accept a propeller which usually would be turned down.

On the question as to whether the vibration effect due to flutter contained itself wholly in the propeller or whether the vibrations came through to the shaft and into the engine system, he knew of no evidence yet to indicate just the type of vibration resulting from flutter.

With regard to feathering on co-axial propellers, he said that when the Brabazon aeroplane was scheduled he and his colleagues were rather worried about what would happen if either half of the propeller of the co-axial type was feathered with the other half rotating either behind or in front of it. Wind tunnel tests had been carried out in conjunction with the R.A.E., and showed that the condition did not increase the drag any more than would the feathering on the propeller on a single-engined installation.

Giving some figures showing the difference of efficiency between the pusher and the tractor types of propeller, Mr. Fairhurst said that with a wing incidence of 1° and a flap angle of 0°, the tractor propeller efficiency was 74%, against the pusher efficiency of 83%; with a wing incidence of 7° and a flap angle of 30°, the efficiencies were 53% and 69% respectively; and with a wing incidence of $7\frac{1}{2}$° and a flap angle of 60°, the efficiencies

were 40% and 66%. Thus, the pusher type gained all the way. Reasons why the tractor type was at a disadvantage to the pusher were due to an earlier breakaway of the boundary layer and also due to the encumbrance of the wing behind the tractor as the drag of the wing was increased by its being in the slipstream of the tractor.

Replying to his preference of the methods of coupled engines to co-axial propellers, Mr. Fairhurst thought that by feathering to a predetermined blade angle any residual rotation of the propeller could be prevented by using a brake; in any case the drag would be very low even with a slight rotation.

*Mr. Griffiths.* Concerning the large diameter propeller curves, he had included them intentionally in order to raise the question, for someone had to say what should be the maximum diameter of propeller for a commercial aeroplane of the multi-engined type. In the case of the 10,000 b.h.p., 40,000 ft., 400 m.p.h. curve, the propeller diameter came out at about 30 ft. In the paper he had mentioned that this figure gave the optimum efficiency; but the curve at that point of optimum efficiency was very flat, so that one could reduce the propeller diameter to 26 ft. or 27 ft. without reducing the efficiency appreciably. He would like to know whether the aircraft designers had any intention of using propellers of 27 ft. diameter.

Reverting to Mr. Owner's query, with regard to Fig. 4, and the suggestion that the diameter of a propeller absorbing 4,000 h.p. at 40,000 ft. was 18½ ft. and not 16 ft., he said that if one included in Fig. 4 the 550 m.p.h. conditions for 4,000 and 5,000 h.p., it would seem that for 4,000 h.p. at 40,000 ft. the propeller diameter would be 15 ft., whereas for 5,000 h.p. at 40,000 ft. it would be 16½ ft. Unfortunately he had not had time to extend the curve to cover 550 m.p.h. conditions.

He had not thought a great deal about triple propellers, mentioned by Mr. Griffiths. There was no doubt that difficulties would be forthcoming on the diameter question. But if another propeller were fitted to the single-engined fighter, it would again introduce torque effect, especially on aircraft operating from fleet carriers, where from the point of view of ease of handling of the aeroplane the counter-rotating propeller had been "sold." The weight would probably come out at about the same.

Without doubt, all propellers should be strain-gauged in flight. On certain installations there had not been a lot of difference between strain gauge recordings when the machines were on the ground and when they were in flight; but in several installations, and particularly in one of them, the vibratory stresses were recorded at the operating r.p.m. and boost for take-off, both when in the air and on the ground, and the stresses recorded when in flight were found to be twice as great as those recorded when the machine was on the ground. In future, flight strain gauging must be insisted upon as essential because, after all, that was the condition in which the machine was used for the greater percentage of its life.

As to the propeller specification for the future, he said he had thought that it was self-contained. However, he was not quite sure what Mr. Griffiths had in mind.

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*Mr. Griffiths said he had in mind removing everything we had to-day on the engine. For example, if there were a big controlling device, it became part and parcel of the propeller, the propeller obviously fitted to the engine shaft, and from there one could arrange a pick-up point for some fixed member on the propeller. One would not then call on the engine for the use of its oil or anything else.*

Mr. Fairhurst replied that this was what he had in mind.

*Mr. Cleaver.* Mr. Cleaver had "hit the nail on the head" when he stated that the author had hoped to obtain the aircraft industry's

reaction to the hypothetical propellers. It was up to the aircraft constructor to state their views on the maximum powered piston-engined fighter, on the maximum propeller diameters which they could accept on multi-engined (wing mounted) machines, and whether or not they had in mind the design of machines with 10,000 b.h.p. at 40,000 ft., propeller-driven.

On the question of thrust augmentation of straight jet installations he considered there was a complete dearth of ducted fan performance data for comparison with pure jet and propeller, as so far all relative curves produced had in the case of the fan been largely "guesstimation." The use of the two-speed gear was without doubt accentuated on gas turbines.

He was in full agreement that difficult problems were ahead in the method of control of propellers on gas turbines, but due to the relative infancy of this unit very little of a practical nature was known. It was hoped that as a result of certain flight tests going on with a propeller capable of constant speeding, feathering, manual control and reversing on a straight jet machine some practical indication of the difficulties would be shown.

On the question of reactionless modes of vibration in the propeller, the author was fully aware of this mode of vibration in propellers beyond three-bladers. According to early published data (mostly estimated) it had shown the five-blade propeller to be a dangerous proposition; this had not, however, deterred the propeller designer from making this type which had been shown to serve a most valuable "stop gap" between four-bladed and counter-rotating propellers, and which was still going on for projected aircraft types. So far, the reactionless modes had not been found to be predominant over the effects of engine torsionals.

Dealing with Mr. Cleaver's query on the vibration and hence, efficiency loss of a counter-rotating propeller with each half running at different speeds and diameters, wind tunnel tests had indicated this to be so.

He considered that further research on the optimum spacing of the two halves of the counter-rotating propeller essential to minimise the higher vibration effects which occurred in the rear half.

*Dr. Watts.* He would like to confirm Dr. Watts' prediction of 1935, but was not of the opinion that 450 m.p.h. was the limit of the propeller-piston engine combination, as aircraft were already flying at 485 m.p.h., without using the fullest aerodynamic propeller technique available.

The use of the two-speed gear, together with the German swept-back blade development could, without doubt, increase this figure. The former enabled a more efficient all-out level rotational speed hitherto not possible, and the latter should increase considerably the critical Mach number of the propeller.

*Mr. Lynam.* He did not agree with Mr. Lynam that the inboard sections were of little consequence, as compressibility losses had been shown to have spread the entire length of the blade. Further, the advent of turbines demanded more than ever very serious consideration of the fineness ratio of root sections to ensure efficient air flow into the compressor.

Increase in spinner size certainly helped, but even at the practical maximum for high speed fighter machines attention to root shapes had been found of paramount importance. On turbines the spinner diameter was essentially small, and as such demanded more care than ever before on root gradings.

On the question of blade materials, he had stated in the paper that a propeller designed basically around duralumin blades would exclude the wood blade alternative and, as such, would come out much nearer to the latter on weight. Dealing with the types of wood blade construction, the compressed

wood feature when used in both blade and root had been shown superior to the natural wood blade and compressed wood root in getting down to the thinner sections and withstanding the higher vibratory effects better in the latest high speed machines. The latter, however, had given most excellent service throughout the war but was limited in its use.

*Group Captain Bulman.* He agreed with Group Captain Bulman that the most desirable condition for application of braking on the propeller on a dive bomber was at any speed and under any condition, but the problems of blade stresses and rates of pitch change had to limit the speed of entering the dive. On the question of the operating condition of top speed receiving primary consideration, it had been the author's experience in several cases that the resulting take-off and climb was impaired, resulting in a last-minute compromise by either increasing rotational speed of the propeller or re-designing the blades.

The advent of the two-speed gear, however, considerably assisted in designing the optimum propeller for the all-out level condition and for the take-off and climb.

*Mr. Hodson.* He was fully cognisant of the valuable research afforded by the Fairey counter-rotating propeller, but had not included this in Fig. 3 since this figure was intended to convey the types which were in production and service use.

In referring to aerodynamic balancing for thrust and torque, the latter balancing feature consisted of balancing the torque forces.

His experience in respect of dynamic balancing tallied with the Fairey Company's experience, except that dynamic balancing was too laborious in any case on production.

*Mr. Snell.* His experience had shown that a wood blade could be made equal to its metal counterpart when considering efficiency under all operating conditions up to 450 m.p.h.

The question of the repair of wooden blades had largely been answered by war-time experiences, wherein large numbers of damaged propellers had been returned to flight, the repairs in many cases having been carried out under the most arduous conditions of service. Experience had also shown that far less damage occurred to the propeller hub and engine reduction gear in a landing crash because the wood blades acted as a safety valve to the mechanism.

In competing with Mr. Snell's duralumin blade in which the pilot brought the machine back from Germany with a hole in the tip, he recalled a particular instance wherein a fighter with a wood blade propeller flying low over the sea removed a portion of the blade tip by striking the water. Nevertheless, he continued his operation and on landing was amazed to see that his propeller had been damaged.

On the question of propeller hubs designed basically for duralumin blades to the exclusion of wood, he did not suggest that this was a hypothetical condition; he stated in the paper that there was little doubt that this could be achieved, being based on actual experience.

He agreed that the question of duralumin blade root designs to avoid concentrations of stress around threads or shoulders, etc., was one of paramount importance.

His suggestions of the relative weights of hollow steel bladed propellers against their compressed wood and duralumin counterparts was purposely on the conservative side, as he was afraid some disappointments were ahead of us when vibratory stresses by strain-gauging were carried out; our previous conception of the hollow blade might change considerably.

On the question of propeller weights, those quoted in the lecture already take account, to a certain extent, of the smaller root and hub size associated with the duralumin blade. Indeed, in order to present a completely fair picture in comparing these weights, those of

duralumin bladed propellers appearing on the curves in question were based upon de Havilland estimates. With regard to Mr. Snell's claim that for larger diameters of propellers even more optimistic weight advantages are shown, the author felt confident that these advantages could be secured. It was only reasonable to expect that, as diameters increased and the weight of blades alone became a greater and greater percentage of the total propeller weight, the propeller having blades of a lower density would score more and more.

Mr. Snell was perfectly correct in his statement that at present the weight of blades represented about 50—60% of the weight of the complete propeller. It was, however, the author's intention to deal rather more with the question of future large diameter propellers where the original statement might be considered substantially correct.

Regarding the criticisms of parts of Figs. 6—9, these were not due to any "un-Fairhurst ingenuity," as suggested by Mr. Snell, but were readily explained on reference to present methods of calculation of propeller efficiency. Had these curves been calculated for single rotating propellers, they would, more or less, have taken the form of radial lines as suggested by Mr. Snell. However, when contra-rotating propellers were considered, an efficiency correction for contra-rotating effect had to be introduced, which had the effect of reducing more and more the diameter required to absorb a given power as the propeller diameter decreased. This had the effect of increasing the slope of the radial lines mentioned previously and producing the criticized gain in power absorption. This criticism, therefore—if there be need for criticism—lay at the door of the contra-rotation efficiency correction. The values of this correction used to-day were based upon the best available information, but were still open to some doubt due to the lack of intensive test data available.

The author's reference to small diameter propellers for turbines was a most definite aircraft requirement, as the reduced undercarriage heights with a straight jet had already "whetted" the appetites of the aircraft designer for similar conditions on the propeller-turbine combination. Reference to greater aircraft control difficulties with "power on" braking against "windmilling" braking was made on account of the former having a greater tendency to reverse slip stream and also in the event of an engine cut with "power on" brakes a very high windmilling speed would occur in a direction opposite to normal rotation.

*Captain Morris.* The author wished to thank Captain Morris for his remarks on the vibration questions, and particularly for his tributes to the collaboration on this subject received from the propeller industry. In turn, he, the author, wished to express on behalf of the industry, their thanks for all the help given by the Establishments on the difficult question of vibration measurement and he hoped that this collaboration would continue.

*Mr. O. N. Lawrence.* No comment was called for on Mr. Lawrence's remarks. The author wished to thank him for an extremely valuable contribution to the discussion, and one which would give much food for thought during future developments on propellers for turbine applications.

*Mr. Nixon.* In reply to Mr. Nixon, the author would like to assure him that the propeller industry have not, by concentrating on military applications throughout the war, shelved problems of prime value to the civil airline operator. Indeed, the universal application of feathering propellers developed in the early stages of the war to meet multi-engined bomber installations had contributed considerably towards the safety feature of civil aircraft. Further, the development of braking propellers for emergency landing carried out throughout the war had again contributed to safer civil aircraft. On the

constructional side, the universal use of strain-gauging for measuring the degree of vibratory stresses in metal blades had also largely contributed towards safer flying by obviating the serious fatigue failures of metal blades.

Mr. Nixon's reference to collaboration between the engine and propeller designers was of paramount importance. He would assure him that on the projected propeller types for the future a very close collaboration was being effected, not only in the constructional side of the propeller but also in the study of the relative dynamic stiffness and effective inertia problems of the engine/propeller system.

Regarding the probable sizes of turbine engines, the curves produced by the author were wholly intended as "bait," and it was gratifying to hear that Mr. Nixon had given consideration to this point by pointing out that six feet was about the maximum diameter envisaged for a turbine unit.

On the question of blade materials, there was little doubt that from the repair point of view the hollow steel blade offered greater problems than either wood or duralumin, but it must be appreciated that on civil airline operation the mortality rate in propellers bore no comparison to military conditions in wartime, and as such the hollow steel blade was bound to score on the grounds of durability.

He agreed that for the small civil aircraft there was room for very considerable development. Automatic propellers for the very small types and manually controlled propellers were already being requested by the aircraft industry in quantities which augurs well when measured in volume of business.

On the question of aerodynamic propeller efficiencies, he would like to assure Mr. Nixon that the aerofoil development carried out during the war has definitely maintained very good propulsive efficiencies in spite of the compressibility problems which with every new mark of fighter became more and more severe.

*Mr. J. V. Inglesby.* Although it was felt by the author that the subject of flutter was rather too large and complex to be treated with any detail in the actual paper itself, some broad remarks in connection with this problem had already been made in reply to Mr. Owner.

Regarding the matter of trouble experienced with brass sheaths on wooden blades and the consequent inability to inspect the screws and rivets, Mr. Inglesby would be pleased to know that every effort was being made to obviate the necessity of using such a sheath.

*Mr. J. A. C. Williams.* Mr. Williams' remarks regarding the probable operating speeds of near-future propellers are undoubtedly correct, but it was his intention in the paper to examine the limiting performance conditions. It was not anticitpated that there would be any difficulty in providing propellers for the lower conditions mentioned by Mr. Williams, but he agreed entirely with the remarks regarding future research work to endeavour to obtain the last ounce of efficiency for civil transport aircraft propellers.

On the subject of noise, it was not his intention to suggest that low cabin noise levels should be attained entirely by absorbing the sound energy between source and the cabin itself. Indeed, such a suggestion would be unreasonable, since the high noise levels of 100—110 db. occurred at the low frequency end of the scale and were extremely difficult to absorb. The question was, therefore, obviously one of reducing noise level at source as Mr. Williams suggested.

THE CHAIRMAN, commenting on a remark that the coming of the atomic bomb and the provision of atomic energy had rendered the future of the large bomber very speculative, said the speaker who had made that remark might have added that the circumstances had rendered the future of everybody very speculative! Its ultimate implications in regard to aircraft could not easily be judged to-day. It

was not merely the fact of being able to carry at high speed, and to drop, an atomic bomb which could do much more damage than anything we knew heretofore; there was also a question which would have a much more profound influence on aircraft design, *i.e.*, the much greater specific energy capacity of the material forming the atomic bomb and which, applied to propulsion, might become another competitor of the jet as we knew it, as it certainly would with the propeller. The future of all types of aircraft was very speculative, bearing in mind the new source of power that was becoming available.

Proposing the hearty thanks of the meeting to Mr. Fairhurst for his paper, which had aroused so spirited a discussion, the Chairman assured him that his written replies to the questions raised would be read with the greatest interest.

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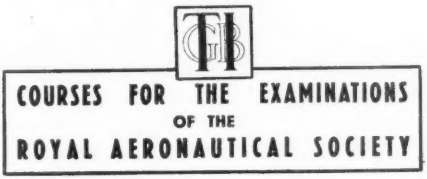


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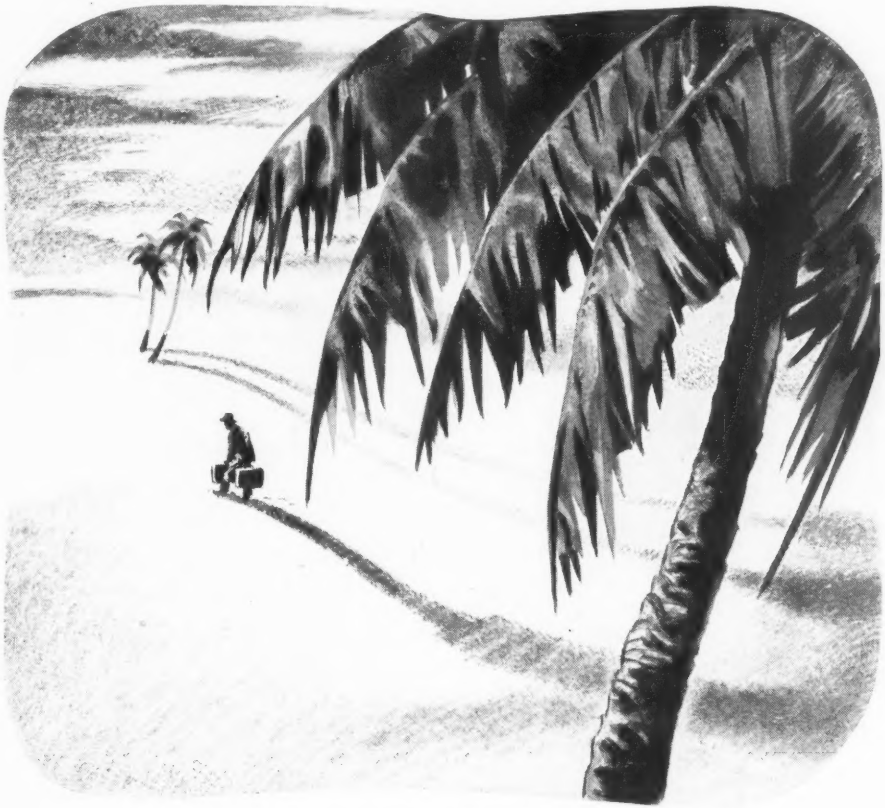

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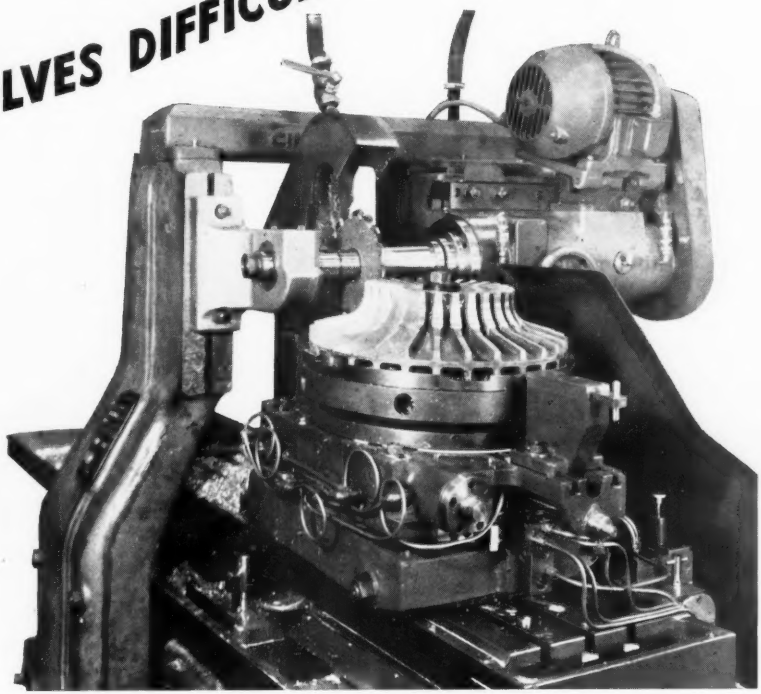

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CHURCHILL-REDMAN LTD. HALIFAX • V. L. CHURCHILL & CO. LTD., WORCESTER

## *A New Industrial Emblem*

**We introduce to you a new industrial emblem which will in future identify the products of this Company. Its style symbolizes the merger of two famous companies and indicates that the vast resources of both are now combined to give even greater service to world industry.**

**BRITISH INSULATED CALLENDER'S CABLES LIMITED**

*Main Works:*

**ERITH, HELSBY, LEIGH (Lancs.) & PRESCOT**

When touching down in a perfect three point landing it's good to know that brakes are FERODO lined . . . ready to take over and bring the plane to rest with velvet smoothness.

*FERODO contributed to the British war effort the Lion's share of all Friction Materials used on land, in the air and on and under the sea. Hence the Lion has become symbolic of FERODO products.*

FERODO
BRAKE LININGS
*For Aircraft*

FERODO LIMITED • CHAPEL-EN-LE-FRITH FERODO

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